Hydrogeology of heterogeneous alluvium in the Leona aquifer,

Caldwell County, Texas

by

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Abstract

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Lloyd Harrison Hemphill, M.S. Geo. Sci.

The University of Texas at Austin, 2005

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The Leona aquifer is an important, but overlooked, water resource in Central Texas. The Quaternary Leona Formation occurs as several isolated alluvial deposits at the margins of the Edwards Plateau. Each of these deposits forms an aquifer. One of these aquifers is located near Lockhart, Texas. This aquifer is recharged by infiltration of precipitation and is discharged by numerous springs and seeps. Additional sources of discharge are evapotranspiration and cross-formational flow into the Wilcox aquifer. The saturated thickness at this location varies seasonally but is rarely greater than 3 m (10 ft).

Groundwater flow in an aquifer of this scale is influenced by its heterogeneous nature. This research identified seven different facies in the Leona Formation and the underlying Wilcox Group. These divisions were based on sediment classification, lithology, and sedimentary structures. The Leona Formation is covered by sandy and silty clay soil and caliche. Each of these facies has different hydraulic properties.

Many empirical relationships between grain size distribution and hydraulic conductivity (K) have been discussed in the literature. Equations developed by Hazen, Slichter, Terzaghi, Beyer, Saurbrei, and Kozeny were used to estimate hydraulic conductivity. Hydraulic conductivity was also measured in the laboratory with constant and falling head permeameters. Hydraulic conductivity of the Leona aquifer varies seven orders of magnitude. Hydraulic conductivity varies up to four orders of magnitude within a single facies due to small-scale differences in grain size distribution and degree of cementation. The arithmetic mean of hydraulic conductivity in vertical profiles through the Leona aquifer ranges from 0.013 cm/sec (37 ft/day) to 0.14 cm/sec (397 ft/day).

Water quality is a concern for many unconfined shallow alluvial aquifers, including the Leona aquifer. Elevated nitrate levels indicate contamination resulting from agricultural land use. Nitrate concentration in the Leona aquifer ranges from 4 ppm nitrate as NO_3 to greater than 70 ppm nitrate as NO_3. These concentrations are significantly greater than those observed in the Wilcox aquifer.

The U.S. Geologic Survey computer code MODFLOW was used to create a groundwater model of the Leona aquifer. In the best simulation, specific yield was 0.1 and horizontal hydraulic conductivity was 0.058 cm/sec (164 ft/day). The simulated hydraulic conductivity is an order of magnitude less than observed in gravel pit outcrops. Modeled recharge was 9 percent of annual precipitation in 2003 and 20 percent of precipitation in the first six months of 2004. Five hypothetical wells were placed in the model to examine the effects of pumping on the aquifer. Wells pumped for 61 days at 0.04 l/sec (0.6 gpm) cause insignificant drawdown while wells pumped at a rate of 3.5 l/sec (55 gpm) cause up to 0.55 m (1.8 ft) of drawdown. Natural drainage of the aquifer caused the water table to decline 0.8 m (2.6 ft) over this same period. MODPATH simulations using this groundwater model indicate an average residence time in the aquifer of 13 years and a maximum residence time of 70 years.

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1. INTRODUCTION

Quaternary alluvial deposits of the Leona Formation are widespread across central and south-central Texas. These deposits can be significant aquifers and an important water resource. The Leona aquifer is also important as a source of recharge to larger aquifers such as the Wilcox aquifer. A wide range of sediment textures and sedimentary structures are seen throughout the aquifer as a result of varying depositional processes. This heterogeneity influences the hydraulic properties of the aquifer.

This research focuses on a deposit of the Leona Formation located in Caldwell and Hays County, Texas. Population growth and development is expected in this area. Aquifer characterization is important for proper use and management of the Leona aquifer. This aquifer plays an important role as a supplemental water resource to the Wilcox aquifer and surface water resources. Seven facies were identified in the Leona Formation and the underlying Wilcox Group based on sediment classification, lithology, and sedimentary structures. The hydraulic conductivity of these facies was estimated using empirical methods and laboratory measurements. Further characterization included measuring the infiltration rate of overlying soils with a ring infiltrometer and Guelph permeameter, estimation of stream discharge, mapping the water table, and monitoring seasonal changes in water levels.

A numerical groundwater model was constructed to estimate recharge, delineate potential flow paths, determine the travel time of particles along the flow paths, and simulate pumping.

1.1 Alluvial Deposits in Texas

Late Tertiary and Quaternary alluvial deposits are important features of the geology of Texas. These alluvial deposits can store significant quantities of water. Early settlers of Texas found these surficial aquifers a convenient source of water because hand dug wells could easily reach the shallow water table. These alluvial deposits continue to be an important resource today, but shallow alluvial aquifers of Texas are easily impacted by agricultural and urban development. Many of these aquifers have been abandoned for deeper aquifers or surface-water resources because of water quality and availability. These alluvial aquifers are susceptible to contaminants from the surface such as nitrates, fertilizers, herbicides, pesticides, and bacteria. They also may be unreliable because the water table may decline considerably during severe drought. Population growth has been significant, especially in central Texas, and is creating a great demand on water resources. It is important to understand these groundwater systems in order to utilize them sustainably and to protect the quality of water that they provide.

Early geologists (Hill and Vaughan, 1898; Weeks, 1945b; Sellards et al., 1947; Byrd, 1971; and others) independently described these alluvial deposits and, consequently, the resulting nomenclature and chronology is complicated. The hydrogeology of the Leona Formation is the focus of this thesis rather than a description of its place in the chronology of alluvial deposits. The Uvalde Formation is discussed briefly because it is an important marker in the chronology of alluvial deposits in Texas and has a definite relation to the Leona Formation. The absolute age of the Uvalde Formation is difficult to define, but it is considered to be late Pliocene or early Pleistocene age (Sellards et al., 1947; and Follet, 1966).

Hill and Vaughan (1898) first used the following description of the Uvalde Formation:

> In the Rio Grande plain lying off the foot of the Balcones Escarpment, from San Gabriel to Devils River, and extending coastward several miles, there is a remarkable geologic formation or series of formations to which the name Uvalde has been given. It consists of a vast deposit of gravel composed almost entirely of rolled flint pebbles, with occasional pieces of limestone, partially embedded in a matrix of chalky marl and clays. Most of these materials have been derived from the decay of the Edwards Limestone of the plateau, and spread like a mantle over the lower

> plain. It caps the higher divides in the Rio Grande plain, and constitutes the highest terrace level in the canyon valley of the plateau.

Hill and Vaughan (1898) also described the Leona Formation:

> The name Leona Formation is proposed for the deposit making the first wide terrace of the Nueces and Leona Rivers, below the level of the Uvalde formation, and for the flood-plain deposit extending westward from the Uvalde on the Leona to the Nueces River. The Leona Formation is a Pleistocene floodplain deposit bearing certain definite relations to the older Uvalde formation and the streams that have laid down its component materials. The Leona may ultimately be correlated with the Onion Creek formation.

Hill and Vaughan (1898) described the Onion Creek Formation as yellow or salmon calcareous marl, occasionally containing fine pebble conglomerate. This formation is derived from the erosion of cretaceous limestone of the Edwards Plateau. It occupies a topographic position below the Uvalde Formation and recent floodplains of secondary streams on the Edwards Plateau. The type locality of the Onion Creek Formation is along Onion Creek near Buda, Texas.

The name Leona Formation has been applied to several deposits outside of the area originally described by Hill and Vaughan. It is often difficult to distinguish between the Leona Formation and the Uvalde Formation in the literature because both names have been used in the past to describe the same deposits. It is also difficult to distinguish between the two formations when only one is preserved, because the relative topographic position is important for identification.

The Leona Formation includes many isolated deposits which accumulated during the same time period. These deposits were laid down by several different drainage systems and may have no connection. Recent alluvium is not always divided from the Leona Formation in the literature. The Leona Formation refers to all alluvium younger than the Uvalde Formation in some of the literature (Welder and Reeves, 1962; and Nee, 1986). Other reports define the Leona Formation as alluvial deposits younger than the Uvalde Formation but older than recent alluvium (DeCook, 1960; Follett, 1966; and Shafer, 1966). The Uvalde Formation, Leona Formation, and recent alluvium may act as a single hydrostratigraphic unit where they are in contact.

The Uvalde Formation and Leona Formation have a definite depositional relationship. The Uvalde Formation was deposited by streams carrying sediment from the Edwards Plateau or farther northwest from the High Plains (Holt, 1956; and Byrd, 1971). These streams have no clear relationship to modern drainage. The Uvalde deposits were dissected by younger streams as base level dropped relative to the land surface. The sediments of the Leona Formation were deposited in these new stream valleys (Weeks, 1933). Modern streams are currently cutting into the Leona terraces. As a result of this deposition and erosion, older terraces typically occupy a higher topographic position. The Leona Formation and other deposits of similar age represent the last major stage of continental deposition north and west of the Gulf Coast (Sellards, et al., 1947). No absolute age has been obtained, but the Leona Formation is considered Pleistocene in age (Hill and Vaughan, 1898; Weeks, 1937; Willis, 1954; and Muller and Price, 1979). The Leona terraces are often found imbedded within older deposits and may include material reworked from these older deposits. This makes it difficult to assign a definite age to the Leona Formation. Most fossils found in this formation have been reworked from Cretaceous formations so they are not beneficial for dating the terraces.

1.2 Comparison of Separate Deposits of the Leona Formation

The Leona Formation is found along modern and ancient rivers on the borders of the Edwards Plateau (Fig. 1.1). This formation has been mapped in Bexar, Caldwell, Concho, Dimmit, Frio, Guadalupe, Hays, Kinney, Medina, Tom Green, Uvalde, Wilson, and Zavala counties in Texas. Although the Leona Formation has been mapped in all of these counties, the only deposits discussed in the literature are located in Caldwell County (Follett, 1966), Hays County (DeCook, 1960), Guadalupe County (Shafer, 1966), Uvalde County (Welder and Reeves, 1962), Medina County (Holt, 1956), Kinney County (Bennett and Sayre, 1962), and Tom Green County (Willis, 1954; Muller and Price, 1979; and Nee, 1986). Other deposits are thin or have little hydrologic significance.

Welder and Reeves (1962) describe the Leona aquifer in Uvalde County, Texas. In this report, the name Leona Formation is used to describe all alluvium younger than the Uvalde gravel. Most of this alluvium was deposited along the Nueces River, Leona River, Frio River, and Sabinal River (Fig. 1.2). The majority of the deposit is a large meander belt from the ancient Nueces River. The Leona Formation in this area is gravel capped with a confining layer of silt and clay. Beneath the Leona River, the gravel forms a highly permeable layer that is 11 m (35 ft) thick and 3 km (10,000 ft) wide. The Leona aquifer reaches its maximum thickness of 30 m (100 ft) in the center of the river valley and thins towards the margins. The saturated thickness of the Leona aquifer is highly variable depending on precipitation. In dry seasons, the water table often drops below the base of the Leona Formation in areas where the underlying beds are permeable. The aquifer is recharged by infiltration of precipitation and losing streams when the water table is low. When the gravel is saturated, springs flow into the Leona River where the clay confining layer has been eroded away. The Leona aquifer also discharges into the underlying Buda Limestone and Austin Chalk. The Leona aquifer in Uvalde County is utilized for domestic use, watering livestock, irrigation, and public supply (TWDB, 2005).

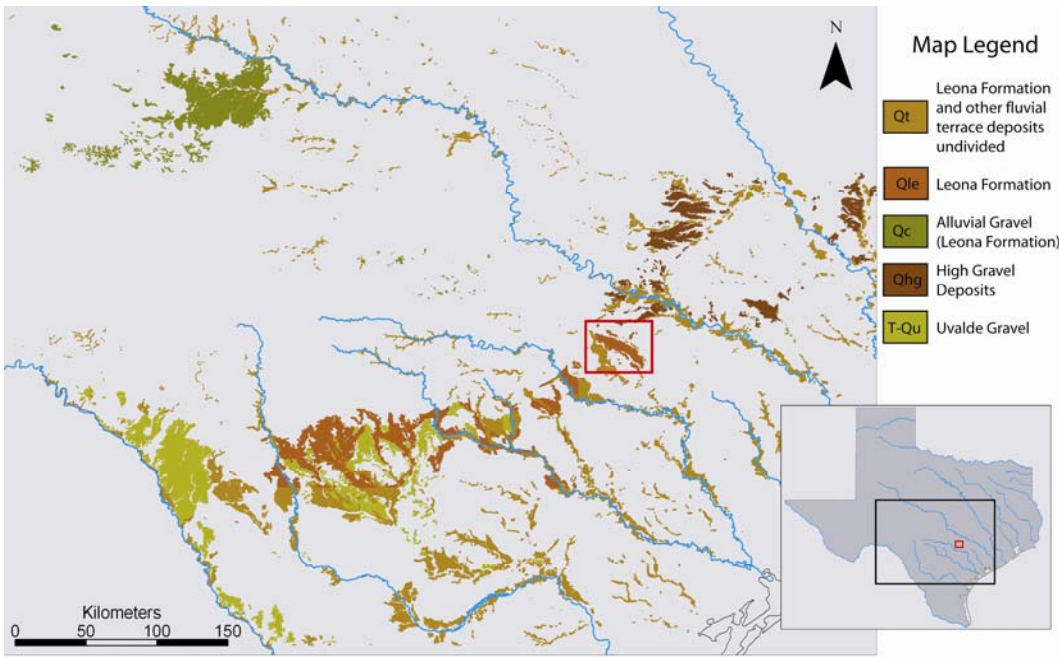


Figure 1.1. The Leona Formation, Uvalde Gravel, and other Quaternary alluvium in Texas. The red rectangle highlights the focus of this research which is a deposit of the Leona Formation near Lockhart, Texas (geology from Barnes, 1974a; Barnes, 1974b; Barnes, 1974c; Barnes, 1976a; Barnes, 1976b; Barnes, 1977; and Barnes, 1983).

Leona aquifer water in Uvalde County is very hard, ranging from 185 ppm to 368 ppm hardness as $CaCO_3$. Nitrate levels range from 1.5 ppm NO_3 to 14.9 ppm NO_3 (TWDB, 2005) and are lower than those observed in other areas.

Holt (1956) discusses deposits of the Leona Formation found in Medina County. Here, the Leona Formation includes broad terraces in present stream valleys that are topographically lower than the Uvalde gravel terrace. Leona terraces cover about 565 km^2 (218 mi.^{2}) along Seco Creek, Verde Creek, San Geronimo Creek, Chacon Creek, Hondo Creek, Medina River, and the Frio River (Fig. 1.2). These terraces are several hundred feet to four miles wide. The Leona Formation in this locality consists of lenticular beds of gravel, sand, silt, and clay. The formation, as a whole, displays an upward fining trend. Gravel clasts are mostly limestone and occasionally chert. The Leona Formation reaches its maximum thickness of 24 m (80 ft) near present stream channels and in abandoned meander channels. The saturated thickness varies depending on the amount of rainfall. The Leona aquifer may be unsaturated where it overlies permeable bedrock because the water table falls below the base of the Leona Formation. Infiltration of rainfall is the main source of recharge into the aquifer. The aquifer discharges to springs and to underlying permeable bedrock. Smaller amounts of water discharge by evapotranspiration and pumping. The Leona aquifer in Medina County is used for domestic, livestock, irrigation, and public supply purposes (TWDB, 2005). Groundwater in the Leona aquifer is very hard, ranging from 116 ppm to 516 ppm of hardness as $CaCO_3$, and contains elevated nitrate, with concentration ranging from 1.5 ppm as NO_3 to 387 ppm as NO_3.

Bennett and Sayre (1962) described deposits of the Leona Formation found in Kinney County, Texas. These deposits were mapped as Uvalde Gravel by Barnes (1977). The Leona Formation forms terraces that are topographically higher than modern flood plains of the Rio Grande, Sycamore Creek, and Las Moras Creek (Fig. 1.2). These deposits are described as alluvial fans extending southward from the Anacacho Mountains. The Anacacho Mountains region is a rugged area of hills and canyons covering approximately 26 km^2 (10 $mi.^2$). This area has a relief of 152 m (500 ft) and is dissected by canyons up to 88 m (290 ft) deep (USGS, 1974; and USGS, 1975). The Leona Formation is topographically lower than Uvalde terraces and is being dissected by modern streams. Limestone gravel, silt, and minor amounts of caliche are found in this deposit. The maximum thickness of the Leona Formation is approximately 9 m (30 ft), and it thins near the boundaries of the deposit. The saturated thickness of the Leona aquifer varies depending on seasonal precipitation. The aquifer may be dry in places during droughts. Infiltration of precipitation is the primary source of recharge. Springs, evapotranspiration, and wells are the sources of discharge. Reported values of total dissolved solids (TDS) range from 157 to 366 ppm, averaging 278 ppm. Total hardness ranges from 117 to 348 ppm. The water in this area is utilized for domestic use, watering livestock, and public supply

(TWDB, 2005). In many areas of Kinney County the Leona Formation and recent alluvium are considered to be a single hydrostratigraphic unit.

Willis (1954), Muller and Price (1979), and Nee (1986) have discussed deposits of the Leona Formation in Tom Green County. These deposits are found north of the Edwards Plateau along the Concho River (Fig. 1.3). These sediments may have been derived from the same source as the Ogallala Formation in the High Plains (Muller and Price, 1979). The Leona Formation is one of the units included in the Lipan aquifer. This deposit of the Leona Formation also extends into Concho County and Runnels County to the east and northeast. Other early Quaternary deposits have also been mapped in the area (Barnes, 1974b). Willis assigns the name Leona Formation to Pleistocene age alluvium overlying Permian bedrock and forms terraces which are 1.5 to 15 m (5 to 50 ft) above younger terraces in the Concho river valley. Nee described these terraces and does not separate the Leona Formation from the recent alluvium. Leona terraces cover 1,036 km^2 (400 $mi.^2$) and are up to 38 m (125 ft) thick. The Leona Formation contains discontinuous beds of poorly sorted, rounded to sub-angular gravel, conglomerate, sand, silty clay, and caliche. Gravel clasts are limestone with smaller amounts of chert and fossil fragments. Sources of recharge are infiltration of rainfall and losing streams. Water levels rise rapidly after heavy rainfall. Muller and Price estimated recharge as 4.6 percent of mean annual precipitation between 1961 and 1975.

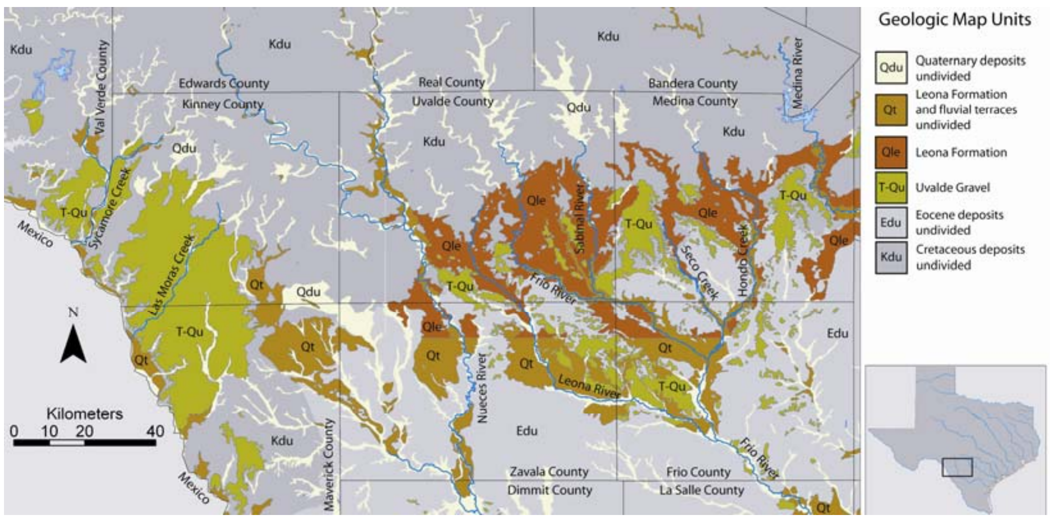


Figure1.2. The Leona Formation, Uvalde Gravel, and other Quaternary alluvium south of the Edwards Plateau. The Leona Formation is not divided from other Quaternary fluvial terraces in parts of Frio County and Zavala County (geology from Barnes, 1976b; Barnes, 1977; and Barnes, 1983).

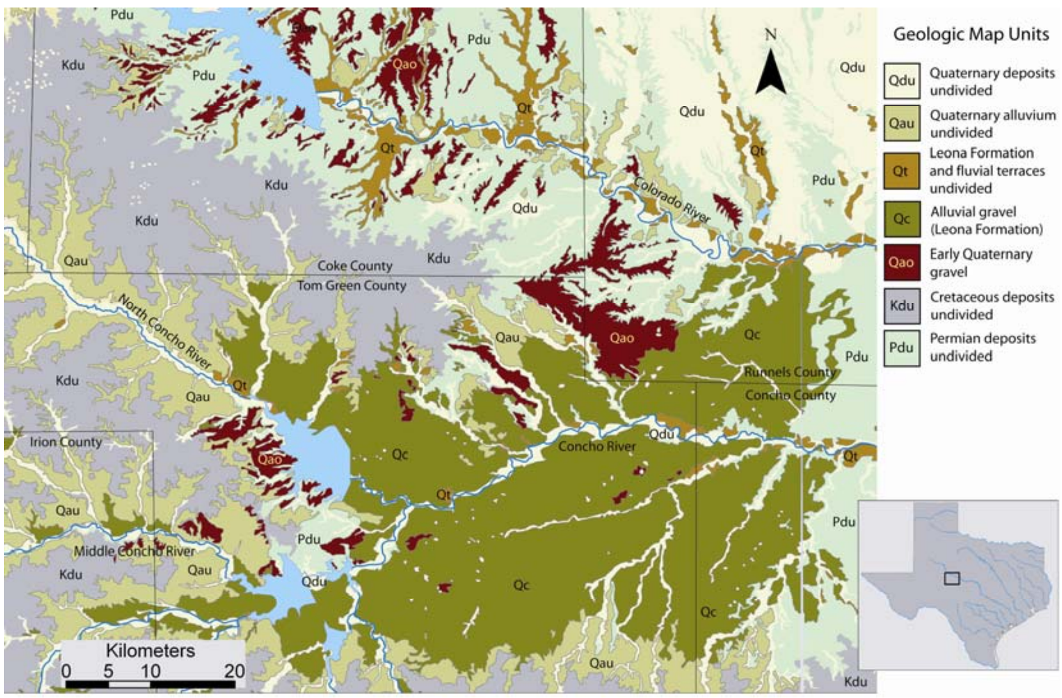


Figure 1.3. Quaternary alluvium north of the Edwards Plateau. Unit Qc (Alluvial gravel) is the Leona Formation (Nee, 1986; geology from Barnes, 1974b; and Barnes, 1976a).

Discharge occurs through springs, evapotranspiration, and pumping. Groundwater in this aquifer is very hard and contains high amounts of dissolved solids. Willis reported TDS values ranging from 500 ppm to 1,400 ppm. Some wells also contain high chloride, sulfate, nitrate, and bacteria levels. Nee tested for herbicides and pesticides, and neither was detected in the groundwater. Generally groundwater quality in Tom Green County has declined over time. Groundwater is utilized for domestic use, watering livestock, irrigation, and public supply (TWDB, 2005). Irrigation wells are found in the thickest portion of the aquifer. Heavy pumping from these wells has caused significant amounts of drawdown over long periods of time. Well yields range from 3 l/sec (50 gpm) to 44 l/sec (700 gpm) although most yield much less than 44 l/sec (700 gpm). The Leona Formation in this area is included in the groundwater availability model (GAM) of the Lipan aquifer developed for the Texas Water Development Board (Beach, et al. 2004).

Shafer (1966) discusses the Leona aquifer in Guadalupe County, Texas. It is described as a broad flat plain with a topographic position between Uvalde gravel terraces and recent floodplain deposits in the Guadalupe River valley. The Leona Formation is also found along Cibolo Creek on the southwest border of Guadalupe County although, in some areas, it has not been differentiated from other Quaternary terraces of Cibolo Creek (Fig. 1.4). The surface of the Leona Formation weathers to black fertile soil. In this area the Leona Formation consists of deposits of cross-bedded gravel and sand with lenses of sand, caliche, and silt. Gravel clasts are limestone with minor amounts of chert and water worn fossils. This deposit has a maximum thickness of 18 m (60 ft), but the saturated thickness is usually less than 5 m (15 ft) depending on the amount of rainfall. The saturated thickness is greatest in river valleys. The primary source of recharge is infiltration of precipitation during wet periods and minor amounts from losing streams. Groundwater discharges from the Leona aquifer through springs, evapotranspiration, and pumping wells. Water also flows from the Leona aquifer into the underlying Austin Chalk and the Wilcox Group bedrock. Groundwater in the Leona aquifer is very hard ranging from 136 ppm to 1,040 ppm of hardness as $CaCO_3$ and may contain elevated nitrate with concentrations ranging from 1.8 ppm NO_3 to 752 ppm NO_3. Contamination by oil brine has also been a problem in the past. The Leona aquifer in Guadalupe County is utilized for domestic use, watering livestock, irrigation, and public supply (TWDB, 2005).

The primary focus of this research is a deposit of the Leona Formation found east of the Edwards Plateau in Hays and Caldwell County (Fig. 1.4). DeCook (1960) and Follett (1966) discuss this deposit in Hays and Caldwell counties, respectively. This deposit is a broad plain 40 km (25 mi.) long and its width varies from 3 km (2 mi.) to 7 km (4.5 mi.). It extends from the city of Kyle to the southeast, past the city of Lockhart (Fig. 1.5). At its highest elevation the Leona terrace is about 30 m (100 ft) above the Blanco River.

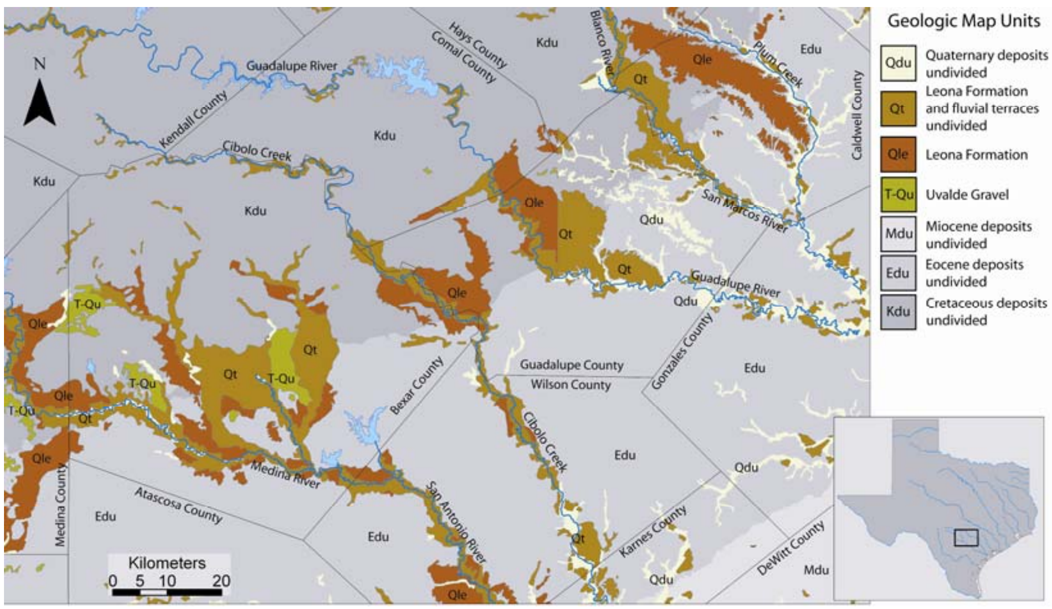


Figure 1.4. The Leona Formation, Uvalde Gravel, and other Quaternary alluvium southeast of the Edwards Plateau. The Leona Formation is undivided from other Quaternary alluvium in parts of Guadalupe County (geology from Barnes, 1974c; and Barnes, 1983).

The terrace has an average slope of 0.25 percent along its northwest - southeast axis and 1.75 percent along its northeast - southwest axis (USGS, 1981; 1994a; 1994b; 1994c.). The Leona terrace is easily distinguished from younger Quaternary terraces because of its higher elevation. In this area, the formation is stratified gravel with some sand, caliche, marl, clay, and silt. In many places, this sediment is very well cemented. The surface of this terrace is covered with fertile black soil which is up to 2 m (6 ft) thick. The lithology of the Leona Formation is discussed in more detail in Section 4.1. This deposit of the Leona Formation reaches its maximum thickness of 12 m (40 ft) in paleo-river channels and thins to a few feet at the margins. The saturated thickness was reported to be less than 3 m (10 ft) by Follet. The aquifer is recharged by the infiltration of precipitation during extended wet periods and by losing streams. The Leona aquifer is drained by gravity springs at margins as well as smaller amounts from evapotranspiration and pumping. Groundwater also discharges into permeable Wilcox Group bedrock. The water is very hard, ranging from 256 ppm to 1,167 ppm of hardness as $CaCO_3$, and contains elevated nitrate, ranging from 5.8 ppm NO_3 to 165 ppm NO_3. Contamination from oil field brine was a problem in the early 1940's according to Follett. Brine from the Larremore oil field (Fig. 1.5) located about 4 km (2.5 mi.) northwest of Lockhart was discharged into ditches excavated in the Leona Formation. The chloride content of groundwater in Lockhart municipal wells reached 1,030 ppm in 1943. The Leona aquifer in Caldwell County is utilized for domestic use, watering livestock, irrigation, and public supply. The cities of Lockhart and Maxwell and the town of Uhland (Fig. 1.5) have used the Leona aquifer as a municipal water supply. In 1953 all of Lockhart's municipal water came from the Leona aquifer. In 1963 about 25 percent of the water supply came from the Leona aquifer and the rest from the Wilcox aquifer. Currently, most municipal water is drawn from the Wilcox aquifer. Follett reported potential well yields ranging from 0 l/sec to 32 l/sec (500 gpm). However, the Leona aquifer can produce much more water over short periods of time. Well # 67-02-903 (Fig. 1.5) is a large collection basin that is 12 m (40 ft) wide, 61 m (200 ft) long, and 4 m (12 ft) deep. Water was pumped out of this pit at a rate of 114 l/sec (1,800 gpm) for about 36 hours and then required 12 hours to refill. The estimated water storage in the Leona aquifer was 50,000 acre-feet during the winter of 1963 to 1964.

Koenig (1940) mapped an upper terrace of the Blanco River. He noted that this terrace coalesces with the broad terrace formed by the Leona Formation. This upper terrace has a maximum thickness of 13 m (42 ft) and is found 18 m (60 ft) to 30 m (100 ft) above the current level of the Blanco River. Koenig hypothesized that the Leona terrace was an abandoned stretch of the Blanco River. Woodruff (1977) proposed that the Blanco River and other major rivers in Texas were pirated by streams at the Balcones Fault Zone.

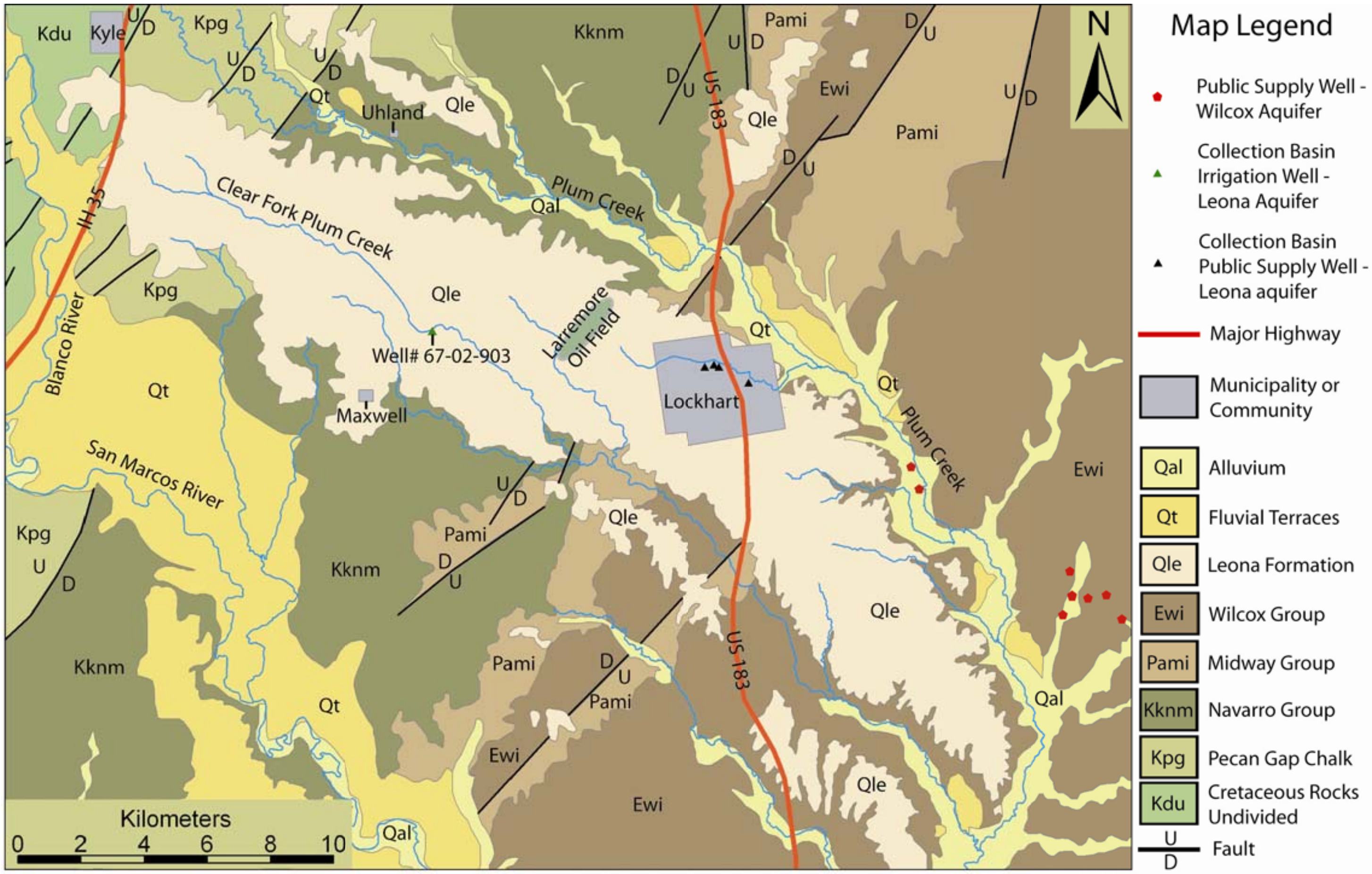


Figure 1.5. Geologic map of the Lockhart study area and the location of Lockhart public supply wells. The original wells are completed in the Leona aquifer and the modern wells are completed in the Wilcox aquifer (geology modified from Barnes, 1974c).

Fault activity steepened the gradient of the land surface and headward eroding streams formed perpendicular to the fault zone. The modern Blanco River flows eastward as it approaches the Balcones Fault Zone. Within the fault zone the Blanco River turns abruptly to the south where it flows into the San Marcos River (Fig 1.6). This right angle bend is the location of the stream piracy discussed by Woodruff. The Leona terrace forms a relatively straight path extending from the right angle bend to the southeast, suggesting that this was the path of the pre-piracy Blanco River.

Many of the high divides in Bastrop County, Bell County, Fayette County, Travis County, and Williamson County are capped by gravel deposits (Fig. 1.7). These deposits may correlate to the Onion Creek Marl, which correlates to the Leona Formation (Barnes, 1974a). Edwards (1974) described one of the high gravel deposits in Williamson County along the San Gabriel River. This deposit forms a raised plain covering 298 km^2 (115 $mi.^2$). It contains upward fining horizontally bedded and cross bedded gravel and sand. Its average thickness is 6.4 m (21 ft) with a maximum thickness of 11.6 m (38 ft). The source of sediment was the Cretaceous bedrock forming the Edwards Plateau, and the gravel is primarily limestone with smaller amounts of chert. The upper portion of the gravel is cemented by caliche and sparry calcite. This gravel deposit forms a shallow unconfined aquifer. Water from this aquifer is used in rural areas for domestic use and for watering livestock.

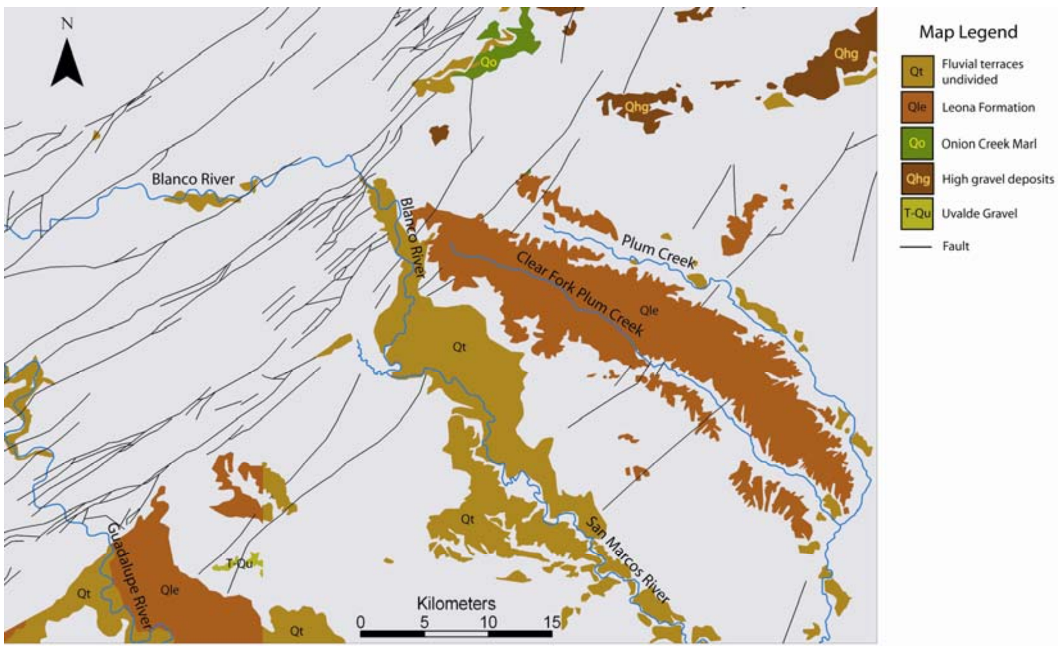


Figure 1.6. Present drainage network in a section of the Guadalupe-Blanco River valley showing evidence of stream piracy. The right angle bend in the Blanco River is the location of a stream piracy event which led to the abandonment of the Leona Formation (geology from Barnes, 1974c; and Barnes, 1983).

The aquifer is recharged by infiltration of precipitation and by influent streams which flow over the outcrop. The aquifer is discharged by evapotranspiration, wells, and springs. The springs are found at the eroded margins of the deposit. These springs discharge up to 100 gpm (6.3 l/sec). Water from this shallow aquifer is less mineralized than deeper water from the Trinity aquifer. Nitrate and coliform contamination is a water quality concern in the shallow aquifer. Nitrate concentration ranges from 10 ppm to 132 ppm and averages 69 ppm. Coliform bacteria are also present suggesting contamination from septic systems.

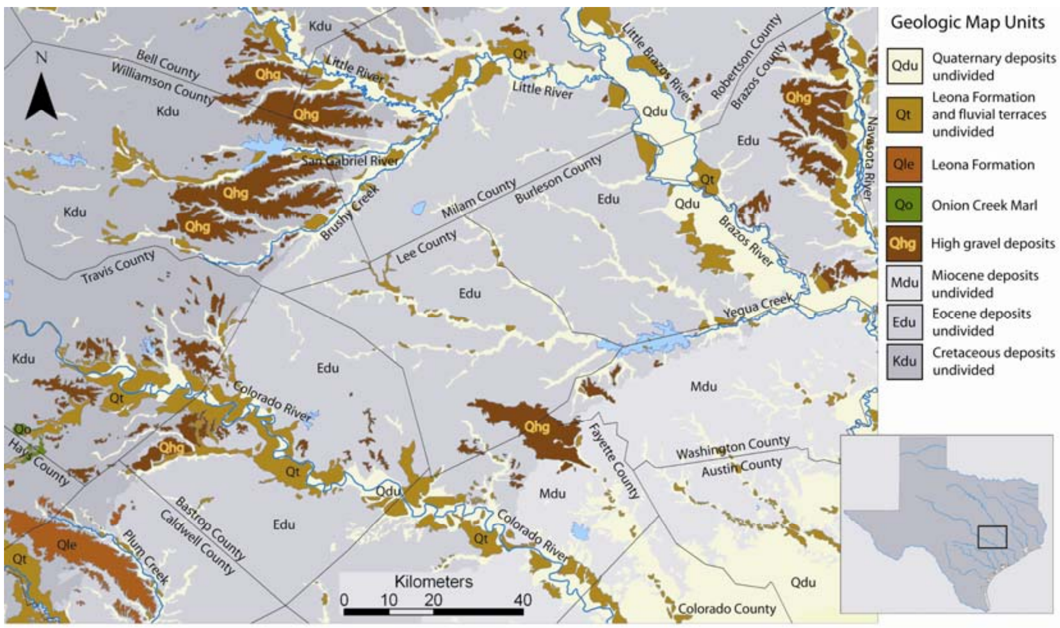


Figure 1.7. The Leona Formation, Onion Creek Marl, and unnamed gravel deposits located on high divides. The high gravel deposits may be either Leona or Uvalde age (geology from Barnes, 1974a; and Barnes, 1974c).

1.3 History of the Lockhart Area and Water Supply

The City of Lockhart is the largest development located over the Leona aquifer in the study area. Byrd Lockhart received the land as payment for survey work completed for the Mexican government in 1830. At this time, settlement was limited by the threat of hostile Comanches. In 1840, Comanches met with Republic of Texas officials to discuss a peace treaty and to negotiate the release of American and Mexican hostages. Fighting broke out during the negotiations and thirty-three Comanches were killed and thirty-two were captured. This fight is known as the Council House fight. Six Americans and one Mexican were killed and ten Americans were wounded. In retaliation for the Council House fight, Comanches raided the towns of Linnville and Victoria and retreated back up the Guadalupe River valley. Texans organized a volunteer army led by General Felix Huston, Colonel Edward Burleson, Captain Matthew Caldwell, and the Texas Rangers. This army overtook the Comanches at Plum Creek near the present site of Lockhart (McKeehan, 2004a; McKeehan, 2004b; and TSHA, 2004). The Texans defeated the Comanche warriors although the Texans were outnumbered. After the Battle of Plum Creek, the area became more hospitable and additional settlers began to establish their home near the Lockhart Springs. Lockhart became the county seat of Caldwell County in 1848. The population of Lockhart in 1858 was 423. In the late 1860's Lockhart became the start of the Chisholm Trail. The population grew to 3,731 in 1920 and to 5,018 in the 1940's, in part due to the discovery of the Luling oilfield (Smyrl, 2003). The population of Lockhart grew to 7,953 in 1980, to 9,205 in 1990, and to 11,615 in 2000 (USCB, 2004). The projected population of Lockhart in year 2020 is 19,105 (WSA, 2004). Lockhart is expected to continue to grow because it is located between rapidly growing Austin and San Antonio.

The streets of Lockhart were first paved in 1928 using gravel from the Leona Formation. At the completion of this early paving project, Lockhart had more miles of paved road than any similar sized town in the United States. (Withers, 1981) The city of Lockhart built its first municipal water works in 1890 utilizing the Leona aquifer. By 1938, the community outgrew this system, and three new municipal wells were completed in the Leona aquifer. The water table in these wells was about 10 m (32 ft) below ground level. At the same time, Lockhart built a new water purification plant and a 300,000 gallon (1,136 m^3) water tower. The purification plant was replaced in 1953, and an additional water tower was built in 1964. Because of unreliability and susceptibility of contamination of the Leona wells, new wells were drilled into the Wilcox aquifer. Currently Lockhart's municipal water supply is from the Wilcox aquifer, and the Leona aquifer is used only in emergencies (Brune, 2002).

1.4 Local Importance as a Water Supply

The Leona aquifer is an important water resource in Caldwell County. Follett (1966) estimated that 50,000 acre-feet of water is stored in the Leona aquifer near Lockhart. It remains the only source of water for many residences in rural areas that have not been reached by networks that supply municipal water or water from a local water cooperation. In some areas, the Leona aquifer may not be dependable as a source of good quality drinking water because it is susceptible to contamination. The Leona aquifer's relatively small saturated thickness also limits its sustainable yield. However, the Leona aquifer is still a valuable resource. Water from the Leona aquifer is viewed as a cheaper source of water, especially by residents who use large amounts of water for lawn and garden irrigation or watering livestock. Many residences use water from the Leona aquifer in addition to water which they purchase from other sources

1.5 Recharge to Wilcox Aquifer

The northwest and up-gradient section of the Leona aquifer overlies the Navarro Group and Midway Group, which contain relatively low permeability units. The southeast portion, the Leona aquifer overlies the more permeable Wilcox Group. Groundwater in the Leona aquifer flows towards the Wilcox Group, and the water table drops below the base of the Leona Formation. The upper part of the Wilcox aquifer is unconfined in this area but clay layers may act as confining layers deeper in the aquifer. Flow from the Leona aquifer helps to replenish water resources in the Wilcox aquifer, which is the largest groundwater resource in the area. Contamination from the Leona aquifer can also enter Wilcox aquifer, although it has been suggested that the quality of water in the Wilcox may be improved when it infiltrates through the Leona aquifer (Follett, 1966).

1.6 Heterogeneity of the Leona Aquifer

The Leona aquifer consists of gravel, sand, silt, and clay. The range of sediments that occur in the Leona aquifer creates a heterogeneous distribution of hydraulic properties. Heterogeneity is also caused by post-depositional processes. Parts of the Leona Formation are well cemented by caliche or sparry calcite. In other areas, especially near the surface, the Leona is highly weathered. Other variability is caused by different types of sedimentary structures such as planar cross bedding, trough cross bedding, and horizontal bedding. Heterogeneity is present on different scales ranging from aquifer scale to grain scale. Minor heterogeneities are important in aquifers such as the Leona aquifer that have a relatively small saturated thickness. Heterogeneity influences groundwater flow to wells completed in the Leona aquifer. Some Leona wells produce large amounts of water and do not go dry in periods of drought. Other nearby wells may produce little water and may often go dry.

Heterogeneity may also change the direction in which groundwater or contaminants travel. Ultimately, it is important to understand aquifer heterogeneity in order to create realistic conceptual models.

2. SETTING

Physiography, geology, climate, and hydrology are important factors which influence the Leona aquifer. Soil, bedrock, precipitation, and streams effect the movement of groundwater into, through, and out of the aquifer. Following is an introduction of these factors.

2.1 Physiography and Geology

Texas contains distinct physiographic provinces (Fig. 2.1). Deposits of the Leona Formation extend from the edge of the Edwards Plateau across the Blackland Prairies into the Interior Coastal Plains. The Leona Formation is also found in the North-Central Plains north of the Edwards Plateau. The Edwards Plateau is a broad plateau, which is capped by resistant Cretaceous limestone and dolomite. The southeastern margin of the plateau is highly dissected by down-cutting streams. Some streams have cut 549 m (1,800 ft) into the plateau (Wermund, 1996). Faulting along the Balcones fault zone on the south and southeast margin of the plateau enhanced the erosion of the streams (Watson, 1982). The Edwards Plateau is a major source of sediment deposited as the Leona Formation.

The Gulf Coastal Plains include three sub-provinces. Nearest to the Gulf of Mexico shoreline is the Coastal Prairies province, which contains grasslands formed on very gently sloping deltaic sands, silts, and clays. Farther inland, is the Interior Coastal Plains province, which contains bands of sand and less resistant shale that weather into gentle ridges and valleys. It contains pine and hardwood forests in eastern Texas and chaparral brush and sparse grasses in western Texas. The subprovince bordering the Edwards Plateau is the Blackland Prairies. Rolling hills are characteristic topographic features in the Blackland Prairies. Chalk and marl bedrock in this province weathers to a thick black clay soil that is very different from the thin red and tan sandy and clay soils found of the Interior Coastal Plains. The soil is fertile and most of the Blackland Prairie is or has been cultivated for crops (Wermund, 1996). The Leona Formation extends across this province into the Interior Coastal Plains. Similar deposits, such as the Uvalde gravel and terraces associated with modern streams, are also found in the Blackland Prairies.

2.1.1 Soils

The Leona aquifer is generally mantled by soil that influences runoff and recharge into the aquifer. Lowther and Werchan (1978) describe 26 different soil series found in Caldwell County. The soils that cover the largest portion of the Leona aquifer and are most relevant to this study belong to the Branyon–Lewisville association. They are the Branyon series, Queeny series, Lewisville series, and Seawillow series. Branyon clay covers approximately 9.1 percent of Caldwell County, Queeny gravelly loam covers 1.3 percent, Lewisville silty clay covers 3.6 percent, and Seawillow clay loam covers 1 percent. The distribution of these soils is shown in Figure 2.2.

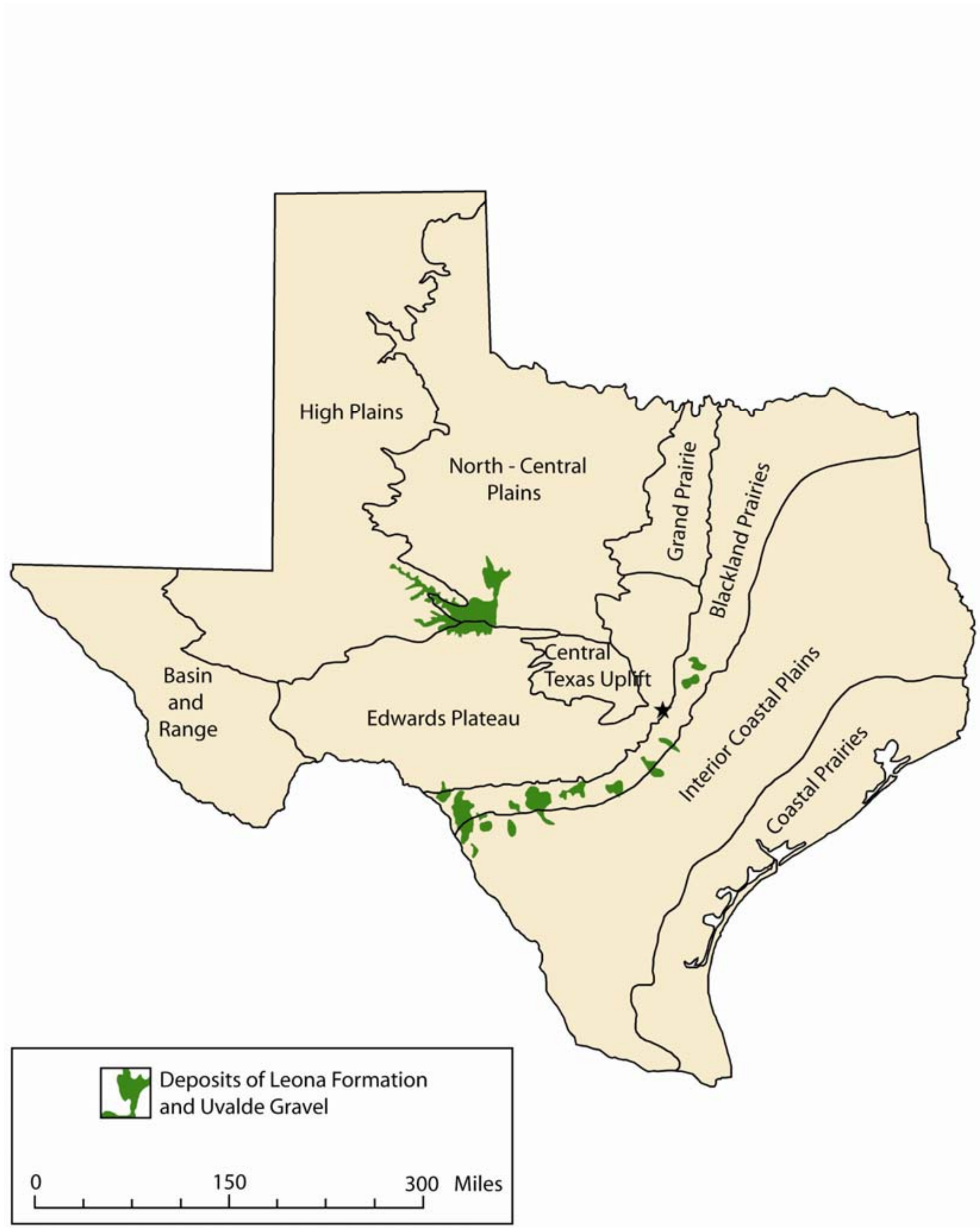


Figure 2.1. Physiographic provinces and location of Leona Formation and Uvalde Gravel in Texas (modified from BEG, 1992; and BEG, 1996).

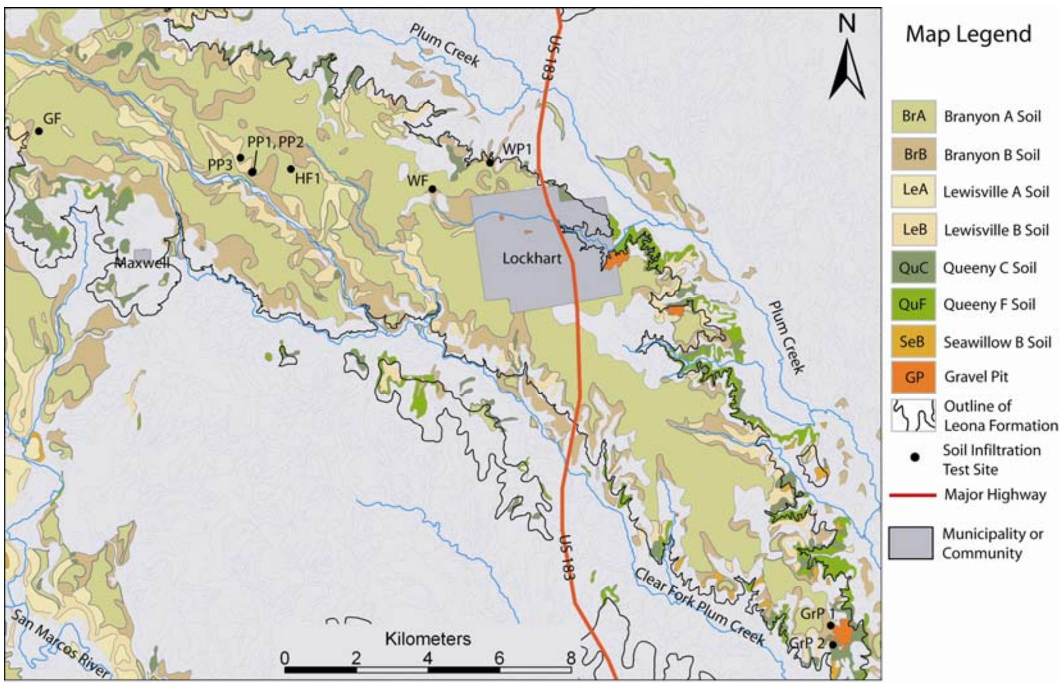


Figure 2.2. Major soils covering the Leona aquifer and the location of soil infiltration test sites (USDA-NRCS, 2004a; 2004b; and 2004c).

The most common soil is the Branyon series which consists of calcareous clay soils overlying old terrace deposits. This series is formed from calcareous clay-rich alluvium. The surface of this soil is about 112 cm (44 in.) of dark gray clay. The next 71 cm (28 in.) is gray clay. The lower horizon is light gray clay. The thickness of Branyon A soil varies but is often greater than 1.8 m (6 ft) thick. The lower 0.6 to 0.9 m (2 to 3 ft) is often 10 to 50 percent by volume gravel and may contain more silt than the upper horizons. Branyon B soils are about 1.4 m (4.5 ft) thick and are underlain by a silty clay layer that is about 30 percent soft masses of calcium carbonate and 40 percent limestone gravel up to 8 cm (3 in.) in diameter. Branyon A soils slope 0 to 1 percent and runoff is slow. Branyon B soils slope 1 to 3 percent and runoff is medium. The U.S. Department of Agriculture (1951) defines runoff potential as the relative rate which water flows over the surface of a soil. This includes rainfall and water seeping from other soils. The six classes of runoff potential (ponded, very slow, slow, medium, rapid, and very rapid) are based on the rate which water flows over the soil surface which depends on the characteristics of the soil profile, soil slope, climate, and land cover. Table 2.1 is a summary of the six classes of runoff potential. Branyon soils have a high available water content ranging from 11 percent to 18 percent. Water infiltrates into this soil very rapidly when dry and very slowly when wet. The permeability near the surface is usually less than

4.2×10^{-5} cm/sec (0.12 ft/day) and near the base ranges from 4.2×10^{-5} cm/sec (0.12 ft/day) to 1.4×10^{-3} cm/sec (4.0 ft/day). Branyon soils have a high shrink-swell potential, and deep desiccation cracks commonly occur during dry periods. The soil properties of Branyon soils are summarized in Table 2.2.

The Queeny series type C (QuC) soils were formed on gravelly alluvium. The surface of this soil is 13 cm (5 in.) to 30 cm (12 in.) of dark gray-brown gravelly loam which is 25 percent by volume limestone and siliceous gravel. This is underlain by around 1.7 m (5.5 ft) of well cemented limestone gravel and sand. The upper 10 cm (4 in) of gravel is well cemented by calcium carbonate. There are also soft masses of calcium carbonate one inch to several feet in diameter. This soil slopes 1 to 5 percent and runoff potential is medium. Queeny C soil has a low available water content ranging from 11 percent to 13 percent in the loamy upper layer and is much lower in the gravel. Permeability ranges from 4.2×10^{-5} cm/sec (0.12 ft/day) to 1.4×10^{-3} cm/sec (4.0 ft/day) in the gravelly loam and 1.4×10^{-3} cm/sec (4.0 ft/day) to 4.2×10^{-3} cm/sec (12 ft/day) in the gravel. Queeny series type F soils are very similar to Queeny C soils but they are found on terrace escarpments which slope 5 to 20 percent and runoff is rapid on Queeny C soils. The soil properties of Queeny soils are summarized in Table 2.2.

Table 2.1. U.S. Department of Agriculture classification of runoff potential (USDA, 1951).

Runoff Potential	Description
Ponded	Precipitation does not escape as runoff. Soil in depressed areas.
Very Slow	Precipitation covers the surface for long periods or immediately enters the soil profile. Most water passes through soil or evaporates. Level or nearly level soil with high infiltration capacity.
Slow	Precipitation covers the surface for significant periods or rapidly enters the soil. Surface water moves very slowly on the soil surface. Most water passes through soil or evaporates. Nearly level or gently sloping soil with high infiltration capacity.
Medium	Precipitation covers the surface for short periods and a moderate proportion enters the soil profile. Most precipitation is absorbed by the soil and used for plant growth, evaporates or moves downward through the soil.
Rapid	Precipitation moves rapidly over the surface and a small part enters the soil profile. Surface water runs off nearly as rapidly as it is added. Moderately steep soil with low infiltration capacity.
Very Rapid	Precipitation moves very rapidly over the surface of the soil and very little enters the soil. Surface water runs off as rapidly as it is added. Steep or very steep soil with low infiltration capacity.

The Lewisville series is found on terraces consisting of calcareous clayey and loamy alluvium. At the surface is approximately 30 cm (12 in.) of dark gray-brown calcareous silty clay. Below this is another 30 cm (12 in.) of dark yellow-brown calcareous silty clay. The next 46 cm (18 in.) is yellow-brown calcareous silty clay loam. Pale brown calcareous clay loam and soft masses and concretions of calcium carbonate are found to about 152 cm (60 in) depth. This soil slopes 0 to 5 percent and runoff is slow to medium. The permeability ranges from 4.2×10^{-4} cm/sec (1.2 ft/day) to 1.4×10^{-3} cm/sec (4.0 ft/day). The available water content ranges from 16 percent to 20 percent. The soil properties of Lewisville soils are summarized in Table 2.2.

The Seawillow series is found on terraces containing calcareous loamy alluvium. At the surface is about 18 cm (7 in.) of gray-brown calcareous clay loam. The next 38 cm (15 in.) is light yellow brown calcareous clay loam and soft masses and concretions of calcium carbonate. Pale brown calcareous loam and soft masses and concretions of calcium carbonate are found to a depth of 154 cm 54 (in.). This soil slopes 1 to 8 percent and runoff is medium. The permeability ranges from 4.2×10^{-4} cm/sec (1.2 ft/day) to 1.4×10^{-3} cm/sec (4.0 ft/day. The available water content ranges 12 percent to 20 percent. The soil properties of Seawillow soils are summarized in Table 2.2.

Table 2.2. Properties of soils covering the Leona aquifer (from Lowther and Werchan, 1978).

Soil Series	USDA Soil Textures	Hydraulic Conductivity (cm/sec)	Available Water Content (%)
Branyon	Clay, silty clay, clay loam, loam, gravelly clay, gravelly loam, and gravel.	$< 4.2\times10^{-5}$ to 1.4×10^{-3}	11 to 18
Queeny	Gravelly loam and gravel.	4.2×10^{-5} to 4.2×10^{-3}	11 to 13
Lewisville	Silty clay, silty clay loam, and clay loam.	4.2×10^{-4} to 1.4×10^{-3}	16 to 20
Seawillow	Clay loam and loam.	4.2×10^{-4} to 1.4×10^{-3}	12 to 20

2.1.2 Stratigraphy

The Leona Formation overlies Cretaceous and younger formations. The Navarro Group, Midway Group, and the Wilcox Group (Fig. 2.3) are the units that subcrop beneath the Leona Formation in the study area. The bedrock generally dips 1 to 2 degrees to the southeast, but locally the dip may be up to 5 or 6 degrees. The strike of the bedrock is essentially parallel to the Balcones Fault Zone (Brucks, 1927; and Collingwood and Rettger, 1926). A cross-sectional view is shown in Figure 2.4.

Pecan Gap Chalk The Pecan Gap Chalk lies in the lower portion of the Taylor Marl. It is blue-gray chalk which grades upward to chalky marl. Its thickness is approximately 61 m (200 ft). The Pecan Gap Chalk is cross cut by faults associated with the Balcones Fault Zone (Barnes, 1974a).

Navarro Group The Navarro Group lies in the upper portion of the Taylor Marl. It consists of upper Cretaceous shallow marine deposits. These are primarily gray-blue clays but also cross-bedded and evenly bedded fine-grained sandstone. In the study area, the Navarro Group averages 198 m (650 ft) in thickness (Sellards, 1924; Collingwood and Rettger, 1926; Brucks, 1927; and Oldani, 1988).

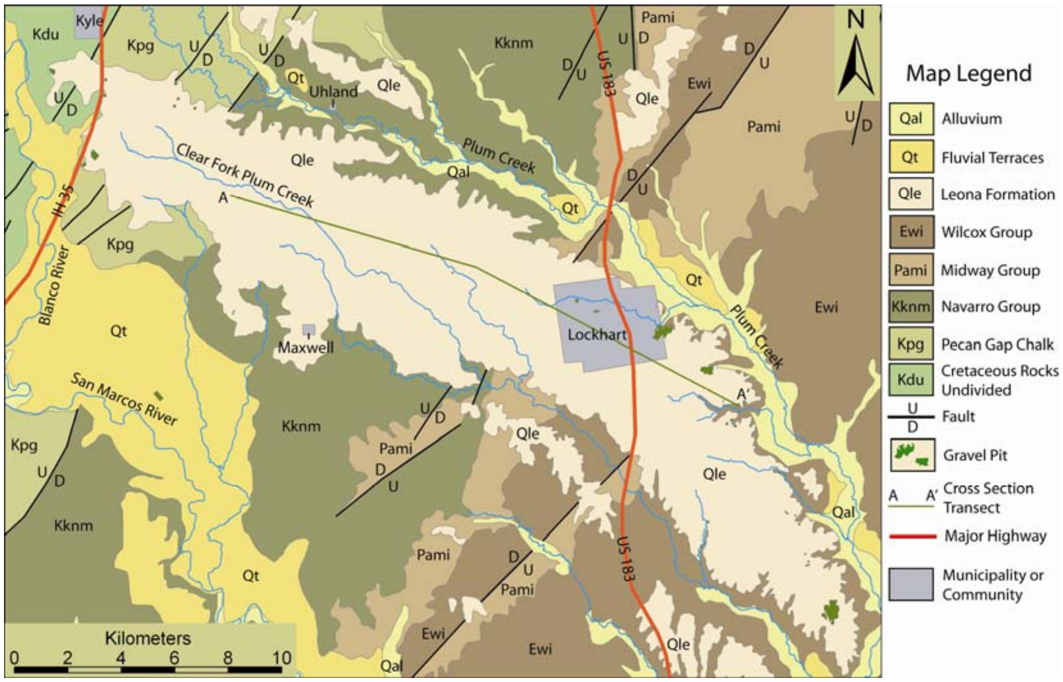


Figure 2.3. Geologic map of the Lockhart study area (after Barnes, 1974c).

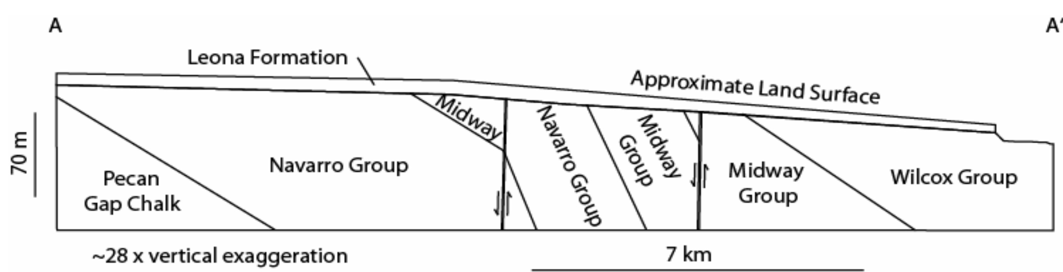


Figure 2.4. Schematic geologic cross section trending northwest-southeast through the Leona Formation and underlying bedrock in Caldwell County, Texas (modified from Follett, 1966).

Midway Group The Paleocene Midway Group is massive gray clay that contains beds of limy concretions with basal glauconitic sand. It represents a transition from the marine deposition of the Navarro Group to the fluvial deposition of the Wilcox Group. Near Lockhart, the Midway Group reaches a thickness of 137 m (450 ft) (Collingwood and Rettger, 1926; Weeks, 1930; and Oldani, 1988).

Wilcox Group The Eocene Wilcox Group is a series of merged deltas. The lower part contains sandy micaceous shale that grades upward into more sandy units of laminated sand and clay and beds of cross stratified sand. The Wilcox Group contains sandy units that are unconsolidated in places and cemented in others. Near Lockhart, the thickness of the Wilcox Group varies from 15 m (50 ft) to 122 m (400 ft). Individual sand beds are up to 31 m (100 ft) thick (Sellards, 1924; Brucks, 1925; Collingwood and Rettger, 1926; and Jones, et al., 1976).

Leona Formation and other Quaternary Alluvium Quaternary alluvium overlies the Pecan Gap Chalk, Navarro Group, Midway Group, and the Wilcox Group. The oldest is the Leona Formation which forms an elevated plain which stretches from Kyle, southeast past Lockhart. Figure 2.5 shows the elevated topography of the Leona terrace. The Leona Formation consists of stratified gravel, sand, silt, and clay. The Leona Formation is discussed in more detail in Section 1.2 and Section 4.1. Younger fluvial terraces are found along the Blanco River, San Marcos River, and Plum Creek. Recent alluvial deposits are found along all of the streams in the area (Barnes, 1974c).

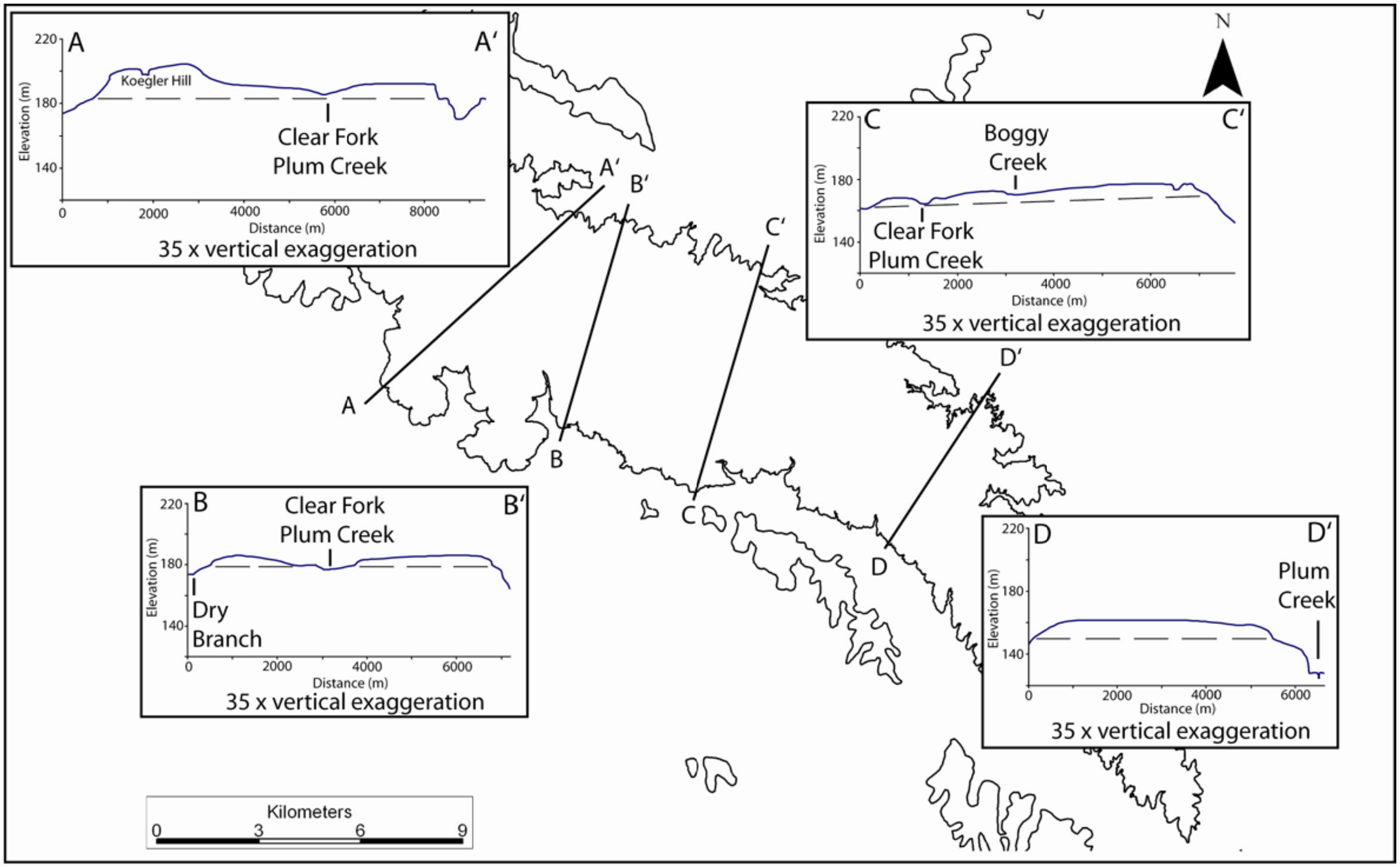


Figure 2.5. Topographic profiles across the Leona Formation (elevation data from USGS, 1981; 1994a; 1994b; 1994c). Dashed lines represent the approximate base of the Leona Formation and were inferred from mapped boundries of the Leona Formation (Barnes, 1974c).

2.1.3 Structure

The Balcones, Luling, and Mexia Fault Zones occur within the study area (Fig. 2.6). These faults are part of the Ouachita structural trend. This structure separates the North American craton from the downwarping Gulf of Mexico Basin (Flawn 1961). The Ouachita trend is an important boundary line in Texas geology and physiography. These three groups of faults are roughly parallel. Movements along the faults in the study area occurred mostly during the Miocene period, but some faulting occurred during the Pliocene and Pleistocene (Weeks, 1945a). The majority of faults in the Balcones Fault Zone are normal faults with the down-thrown side to the southeast (Brucks, 1927). The Balcones Fault Zone separates the relatively flat lying rocks of the Edwards Plateau from the more steeply dipping beds of the Gulf Coastal Plain (Weeks, 1945b). The Luling Fault Zone is southeast of the Balcones Fault Zone. This zone contains faults where the down-thrown side is to the northwest (Weeks, 1945a). The wells in the Luling oil field are producing oil from structures associated with the Luling Fault Zone. The Mexia Fault Zone is a series of horsts and grabens located east and northheast of the Luling Fault Zone (Weeks, 1945a).

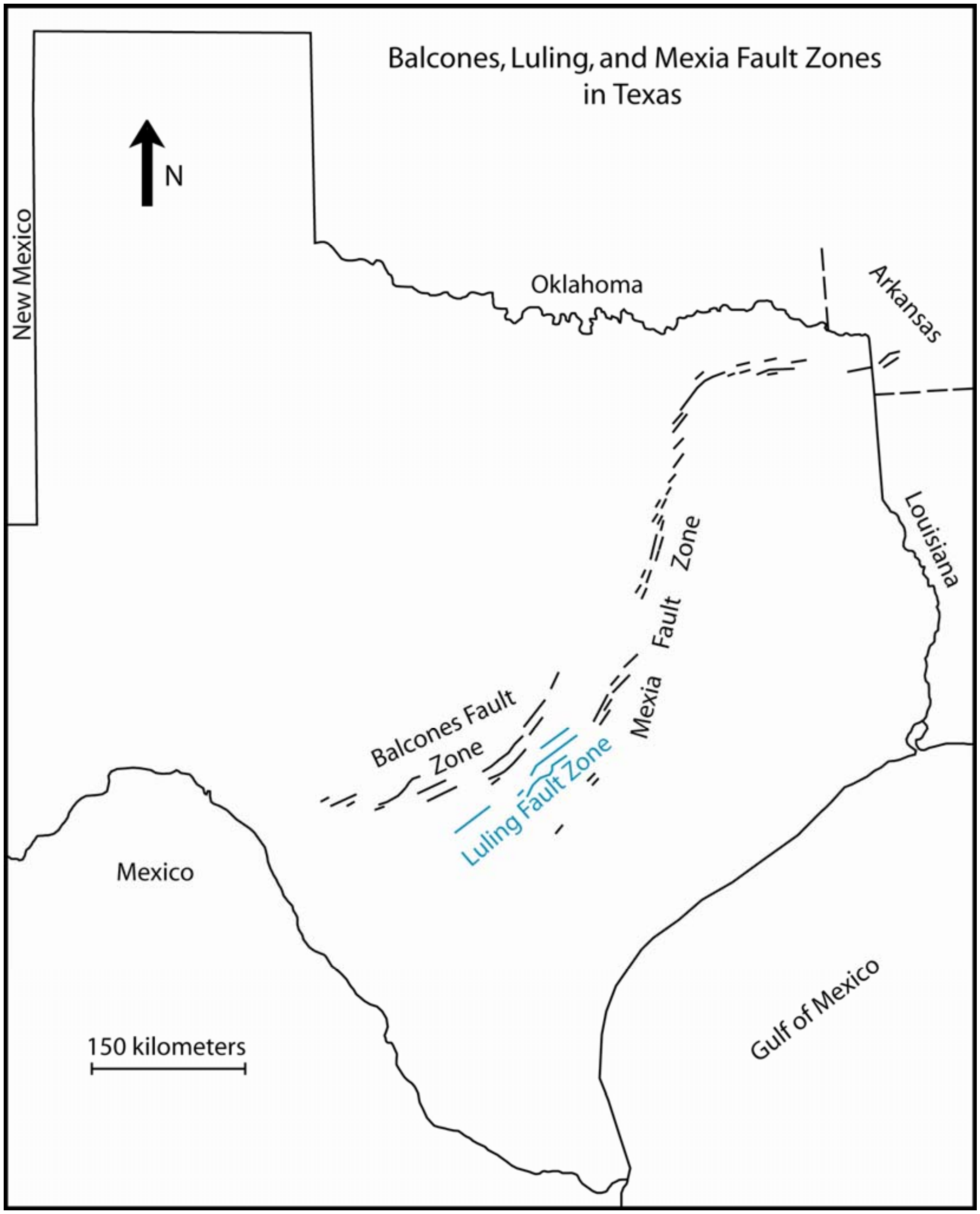


Figure 2.6. Balcones, Luling, and Mexia fault zones in Texas (modified from Weeks, 1945a).

2.2 Climate and Hydrology

Climate and hydrology are important factors influencing the Leona aquifer. These factors are different depending on the location. The climate and hydrology of the Lockhart study area are discussed in this section.

2.2.1 Climate

The climate of Caldwell County is humid-subtropical with hot summer months and mild winter months. Based on temperature recorded in Luling, Texas from 1941 to 1970, the coldest month is January with average minimum and maximum daily temperatures of 38.1 ºF (3.4 ºC) and 61.2 ºF (16.2 ºC). The hottest month is August with average minimum and maximum daily temperatures of 72.2 ºF (22.3 ºC) and 97.4 ºF (36.3 ºC). The warm season is on average 275 days long with the first freeze around November 29 and the last freeze around February 27 (Lowther and Werchan, 1978).

From 1947 to 2001 the mean annual rainfall measured in Lockhart, Texas was 864 mm (34.0 in.). The wettest year was 1960, when the total annual rainfall was 1,324 mm (52.1 in.). The driest year was 1954 with only 353 mm (13.9 in) of precipitation (NCDC, 2004). Typically the four wettest months are May, June, September, and October (NCDC, 2004). There are two different causes of elevated precipitation during these four months. Convective thunderstorm activity peaks in May and continues into June. Precipitation is initiated when moist Gulf air encounters cool northerly airflow. Hurricanes are an occasional source of precipitation in central Texas. The largest hurricanes to hit the Texas coast have occurred in September. Some of the heaviest rainfall recorded in Texas has occurred when remnants of Gulf Coast hurricanes reach the Balcones escarpment (Carr, 1967). The driest month is normally July (NCDC, 2004) when warm high pressure cells form over central Texas and suppress precipitation (Carr, 1967).

2.2.2 Streams

Plum Creek, Clear Fork Plum Creek, Dry Branch, Town Branch, and Boggy Creek are the largest streams in the area (Fig. 2.7). The upper reaches of these streams are intermittent; they are often dry in dry summer months. The raised Leona terrace lies between the valleys of Plum Creek and Clear Fork Plum Creek. Plum Creek is the largest stream adjacent to the Leona aquifer. Since 1960, the daily mean flow in Plum Creek at a USGS gauging station north of Lockhart, Texas has ranged from 0 l/sec to 41,626 l/sec (1,470 cfs) and the mean flow was 1,235 l/sec (43.6 cfs). A portion of this stream flow is runoff from the Leona terrace and discharge from the aquifer. Several tributaries of Plum Creek also contribute stream flow from areas unrelated to the Leona aquifer. Plum Creek drains into the San Marcos River to the south near Luling, Texas. Clear Fork Plum Creek, Dry Branch, Town Branch, and Boggy Creek are fed principally by springs flowing from the Leona aquifer. Stream flow was estimated in July of 2004 and is discussed in Sec. 3.4.

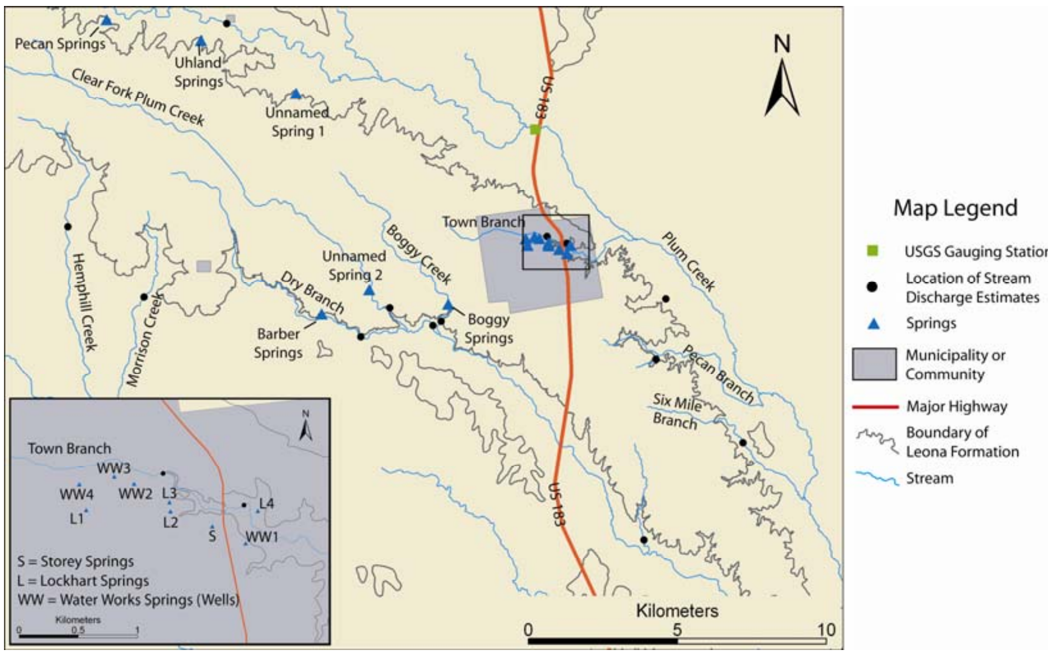


Figure 2.7. Drainage network carrying runoff and discharge away from the Leona aquifer, major springs, and locations of stream discharge estimates.

2.2.3 Springs

A number of springs flow from the base of Leona Formation where it overlies impermeable bedrock (Fig. 2.7). Several of these springs are found in Lockhart, Texas. These springs attracted settlers to the present location of Lockhart. Storey Springs and four springs called the Lockhart Springs feed Town Branch, which flows through Lockhart. Storey Springs is known locally as the site where Sam Houston gave a speech in 1857. The Water Works springs are another group of springs found in Lockhart. These springs were an early municipal water supply. They were dug out to increase their flow. The largest is a pit 10 m (33 ft) wide 66 m (217 ft) long and 8 m (26 ft) deep. Boggy Springs is located about 4 km (2.5 mi.) southwest of Lockhart. Numerous seeps form a boggy area covering several acres. These springs flow into Boggy Creek. The combined discharge in Boggy Creek reached 19 l/sec (0.67 cfs) in 1946 (Brune, 2002) and during drought conditions on December 13, 1999, the discharge was 10 l/sec (0.35 cfs) (Hauwert, 1999). Pecan Springs and Uhland Springs are two groups of springs found near the community of Uhland. These springs were an early municipal water supply for Uhland. Historical spring discharge of these springs and others are displayed in Table 2.3. Many smaller springs and seeps flow from the margins of the Leona aquifer and along streambeds.

Table 2.3. Historical spring discharge from the Leona aquifer (from Hauwert, 1999; Brune, 2002; and TWDB, 2005)

		Historical Spring Discharge	
Name	Year	(cfs)	(l/sec)
Pecan Springs	1975	0.07	1.9
Uhland Springs	1975	0.03	0.9
Unnamed Springs 1	1963	0.01	0.3
Unnamed Springs 2	na.	na.	na.
Barber Springs	1964	0.00	0.0
Boggy Springs	1946	0.67	18.9
	1964	0.04	1.3
	1975	0.35	10.0
	1999	0.35	9.8
Lockhart Springs 1	1977	0.12	3.5
Lockhart Springs 2	1977	0.11	3.0
Lockhart Springs 3	1977	0.11	3.0
Lockhart Springs 4	1946	0.22	6.3
	1975	0.35	10.0
Storey Springs	1977	0.11	3.2
Water Works Springs (wells)	na.	na.	na.
na. = spring discharge data not available.			

3. METHODS

The Leona aquifer in Hays and Caldwell County lies within a developing region between Austin and San Antonio. Following a plan for sustainable use and preserving the quality of the Leona aquifer should be a part of this development. The heterogeneous lithology and hydraulic properties, seasonal changes in aquifer levels, annual recharge, and groundwater contaminants, such as nitrate, are important issues. This investigation of the Leona aquifer included grain size analysis and sediment classification of outcrop samples, estimation of hydraulic conductivity using empirical methods, laboratory and field measurements of permeability, water well inventory, recording water level changes over time, estimation of stream discharge, analysis of basic water chemistry (TDS, pH, temperature, and nitrate), and groundwater flow modeling

3.1 Aquifer Characterization

Direct information about the Leona aquifer alluvium is limited to outcrops and a small number of logs from water well driller's reports. The best outcrops of the Leona Formation are in gravel pits (Fig. 3.1), although a few small exposures were found in roadside ditches. The gravel pits are dug into the unsaturated zone and the water table was only observed in the bottom of the deepest pits. Gravel pits only penetrate the full thickness of the Leona Formation to the southeast where the water table drops below the Leona Formation into the Wilcox Group.

In other areas, where the water table is shallow, only a few meters of the Leona Formation are exposed. The assumption is made that the unsaturated areas of the Leona aquifer are analogous to the saturated areas. However, it must be realized that this may provide a bias. For practical reasons, gravel pits are only located in the areas with highest concentrations of gravel, in a zone that is unsaturated, and close to transportation access.

The Leona aquifer consists of gravel, sand, and clay layers. Lithologic facies are useful for describing the aquifer's heterogeneity. Bedding thickness, sedimentary structures, degree of cementation, grain-size, and lithology were observed in the field. Stratigraphic sections were drawn to represent the larger outcrops. The Leona aquifer was divided into seven lithofacies based on grain lithology, grain-size distribution, and sedimentary structures. Each of these attributes represents different depositional processes. Many of the facies are lenticular and, on the outcrop scale, lateral variability is significant. Stratigraphic profiles which were drawn at different locations on the same outcrop show different distribution of facies. The geometry and distribution of these facies were mapped on photographs of outcrops to describe the vertical and horizontal variability. Representative samples were collected from each lithofacies to estimate hydraulic conductivity.

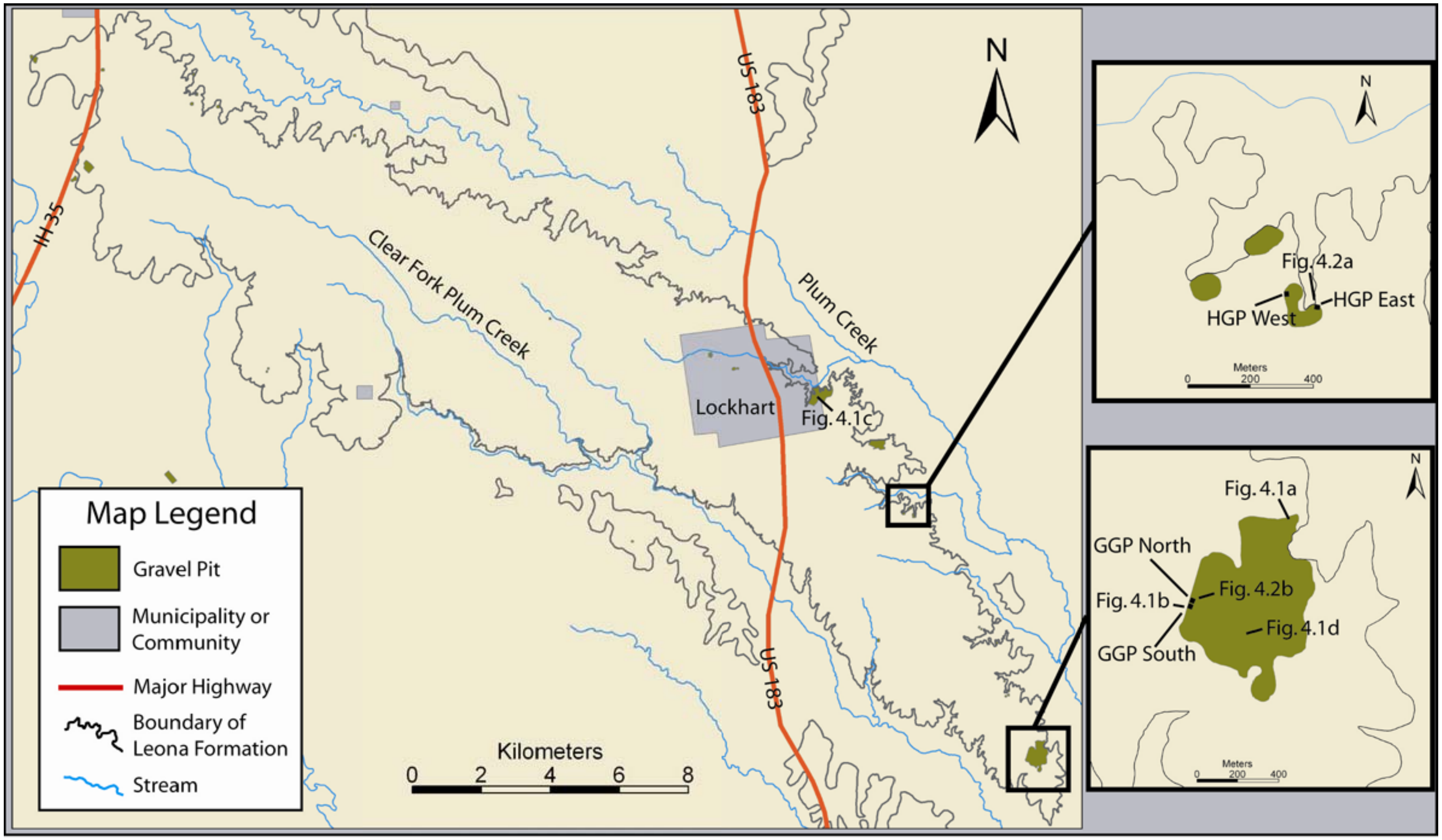


Figure 3.1. Operating and abandoned gravel pits in the Lockhart study area. The inset maps show pits which were studied in this research and locations of photographs of typical facies discussed in Section 4.1 (gravel pit locations from USGS, 1981, 1994, 1994, and 1994).

3.2 Hydraulic Estimates

Estimating hydraulic conductivity is an important part of the characterization of the Leona aquifer. Lithofacies were identified on the outcrop based on grain lithology, grain-size distribution, and sedimentary structures and mapped on outcrop photographs. Samples were collected from each facies for grain size analysis, sediment classification, and laboratory measurement of permeability. Other estimates were obtained using empirical relationships between hydraulic conductivity and grain-size distribution. The permeability of soil covering the aquifer was measured using a ring infiltrometer and Guelph permeameter.

3.2.1 Sample Collection

In the initial phase of sampling, grab samples were collected from all of the facies. The purpose of these samples was to perform grain-size analyses and obtain empirical estimates of hydraulic conductivity. Grain-size analysis of well cemented samples was not possible, because individual clasts could not be separated without reducing their grain-size. Samples collected for grain-size analyses must be large enough to be representative of the facies. AASHTO T-88 (2000) suggests that at least 2 kg (4.4 lbs) of sediment be sieved when the diameter of the largest grains are 25 mm (1 in.). Sand or clay samples with no gravel require less than 0.5 kg (1.1 lbs) of sediment.

A second round of sampling was conducted to collect samples for measuring permeability in the laboratory. When collecting samples to take into the laboratory, it is important to preserve or be able to recreate *in situ* conditions. These conditions include packing and orientation of clasts and the degree of cementation. Where possible, samples were collected as undisturbed blocks. Where uncemented or poorly cemented samples were too fragile to extract intact, disturbed samples were collected. An attempt was made to estimate bulk density in the field using a method similar to the one described by Blake and Hartge (1986). This method involves carefully carving out the sediment and measuring the resulting void. This was difficult to accomplish due to the large grain size and the cemented, yet fragile, nature of most of the material. As a result, it was not possible to obtain adequate estimates of bulk density in situ.

3.2.2 Laboratory Measurements

Permeability is measured in the laboratory with several different types of permeameters. Darcy (1856) conducted the first permeameter experiments in order to measure the flow of water through different sand filters typically used in public fountains. These experiments resulted in Darcy's Law, which is expressed as:

$$Q = -KIA \qquad 3.1$$

where Q is the discharge from the sample (L^3/T), K is hydraulic conductivity (L/T), I is the hydraulic head gradient (-), and A is the cross sectional area of the sample (L^2). In the laboratory, constant head permeameters are used for samples with higher hydraulic conductivities and the falling head permeameter for samples with lower hydraulic conductivities.

Measuring permeability in the laboratory has both advantages and disadvantages when compared with either empirical methods or field methods. The laboratory is a controlled environment. Variables such as hydraulic head and water temperature are much easier to control in the laboratory than the field. If undisturbed samples are used, permeability measurements account for factors such as grain size, grain shape, the orientation of grains, bulk density, cementation, and sedimentary structures. Empirical methods approximate some of these factors but ignore others. Laboratory measurement of permeability also has some drawbacks. Sample size is usually limited by the logistics of transporting them from the field to the laboratory or by the laboratory equipment being used. Laboratory samples are not representative of larger scale sedimentary structures or stratigraphic layering in an aquifer. Preparing samples to be installed into laboratory permeameters also may be time consuming. Field methods such as pumping tests measure a more representative portion of the aquifer but require more time and labor.

Constant Head Permeameter One method of obtaining permeability data is through laboratory measurements using a constant head permeameter that measures permeability by inducing a flow of water through a sample while maintaining a constant hydraulic head. Water flows through the sample from the constant head reservoir. The water exiting the sample is collected during a timed interval in order to calculate the rate of discharge. The head gradient is measured with two manometers, at the top and bottom of the sample. Hydraulic conductivity is calculated from Darcy's Law, which is only valid for laminar flow. A plot of Darcy velocity vs. hydraulic gradient verifies that laminar flow conditions are present. Darcy velocity, or specific discharge, is the discharge (Q) through the sample's cross sectional area (A). A linear trendline should fit the data points and intersect at the origin. The constant head pemeameter was designed so that the height of the constant head reservoir was variable in order to adjust the hydraulic gradient. Multiple tests were run at each hydraulic gradient.

A custom permeameter (Fig. 3.2) was used which is similar to one described in ASTM standard (D 2434-68) (ASTM, 2003a). This standard suggests that the diameter of the permeameter chamber should be at least 8 to 12 times larger than the diameter of the largest grain size, in order to obtain measurements for a representative volume. The permeameter built for this study is 15 cm (6 in.) in diameter. Clasts in the Leona Formation are occasionally greater than 8 cm (3 in) in diameter although the majority are smaller than 19 mm (0.75 in). Samples were held in place in the permeameter chamber with 8 mm (0.31 in.) mesh metal screen and fine nylon screen.

Undisturbed samples provide the most representative measurements of permeability. Large blocks of cemented sediment were collected. These blocks of sediment were trimmed to fit inside of the permeameter. Next, the samples were coated with plaster of paris and placed into the permeameter chamber. The space between the sample and cylinder was filled with molten wax to form a tight seal. The plaster of paris coating was used to prevent the molten wax from flowing into the sample and filling the pore spaces.

In the case of uncemented or poorly cemented samples, it was impossible to collect undisturbed samples. Grab samples were collected and repacked into the permeameter cylinder. It is impossible to recreate natural packing patterns and sedimentary structures using this method. When using samples with large gravel, it is also difficult to eliminate exaggerated void spaces at the edge of the cylinder. Disturbed samples were packed into the permeameter as densely as possible to approximate the bulk density of samples containing gravel sized particles.

Falling Head Permeameter A falling head permeameter was used to measure the permeability of samples with lower permeability. The small volume of discharge through these samples requires more accurate measurement techniques. Samples were prepared and installed in the permeameter using the same procedure described for the constant head permeameter. The constant head reservoir was replaced by graduated glass tubing.

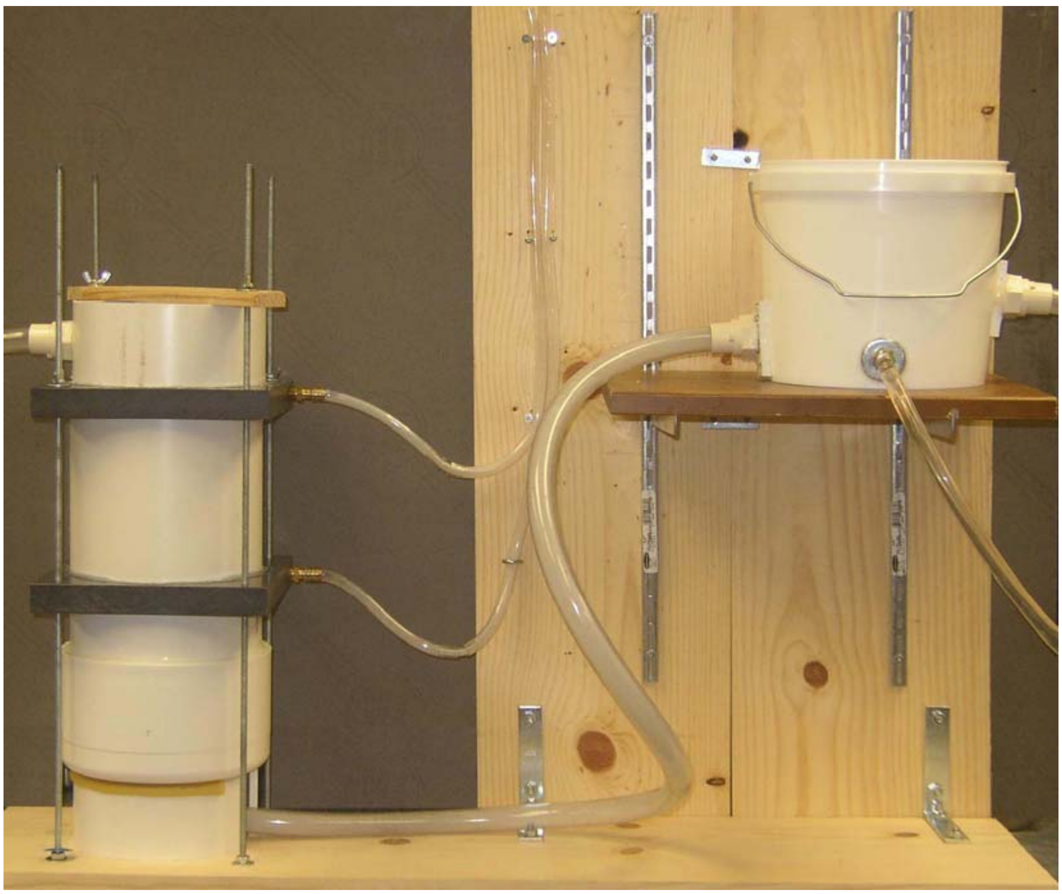


Figure 3.2. Constant head permeameter used to measure the permeability of samples from the Leona aquifer and Wilcox aquifer.

This tubing was filled with water so that the hydraulic head was greater than the head at the top of the sample. Discharge was measured by observing the head drop in this glass tubing.

3.2.3 Grain-size Analysis

Grain-size distributions were determined in order to obtain empirical estimates of permeability. Sieve and hydrometer analyses were performed on all samples except well cemented samples. The grain-size analyses were completed using the methodology described by American Society for Testing and Material (ASTM) standard D 422-63 (ASTM, 2003b). ASTME-11 sieve numbers 3", 2", 1.5", 1", ¾", 3/8", 4, 10, 16, 30, 50, 100, 200, and 270 were used for the sieve analyses and an ASTM 151H hydrometer was used for the analysis of sediment finer than the No. 270 sieve. Additional details describing the procedure of grain-size analyses can be found in ASTM standard D 422-63 (ASTM, 2003b).

Empirical Relationships Hydraulic conductivity is influenced by the size, shape, sorting, packing, and degree of cementation of particles in a porous media. Several different empirical relationships have been developed to describe how some of these factors influence hydraulic conductivity. This study used empirical relationships developed by Hazen, Slichter, Terzaghi, Beyer, Sauerbrei, and Kozeny.

Vukovic and Soro (1992) presented these six relationships using the following dimensionally homogeneous equation:

$$K = \left(\frac{g}{v}\right) * C * \varphi(n) * d_e^{\,2} \qquad 3.2$$

where: K (L/T) is hydraulic conductivity, g (L/T^2) is the acceleration due to gravity, v (L^2/T) is kinematic viscosity, C is a dimensionless coefficient, φ(n) is a function of porosity, and d_e (L) is an effective grain diameter. These variables are calculated differently depending on the method which is used (Table 3.1).

Each empirical method was developed using particular types of sediment. Using an empirical method for coarser sediment, finer sediment, or poorly sorted sediment may not produce the best estimates. The intended range of applicability for each method is listed in Table 3.1. Notice that sediments with gravel and clay sized particles are out of the range of applicability for many of these methods. Empirical methods also do not account for variable permeability due to cements or sedimentary structures. Sampling and performing grain-size analyses are relatively easy making empirical methods ideal for collecting quick and inexpensive estimates of hydraulic conductivity.

Table 3.1. Parameters included in empirical relationships between grain-size distribution and permeability (modified from Vukovic and Soro, 1992).

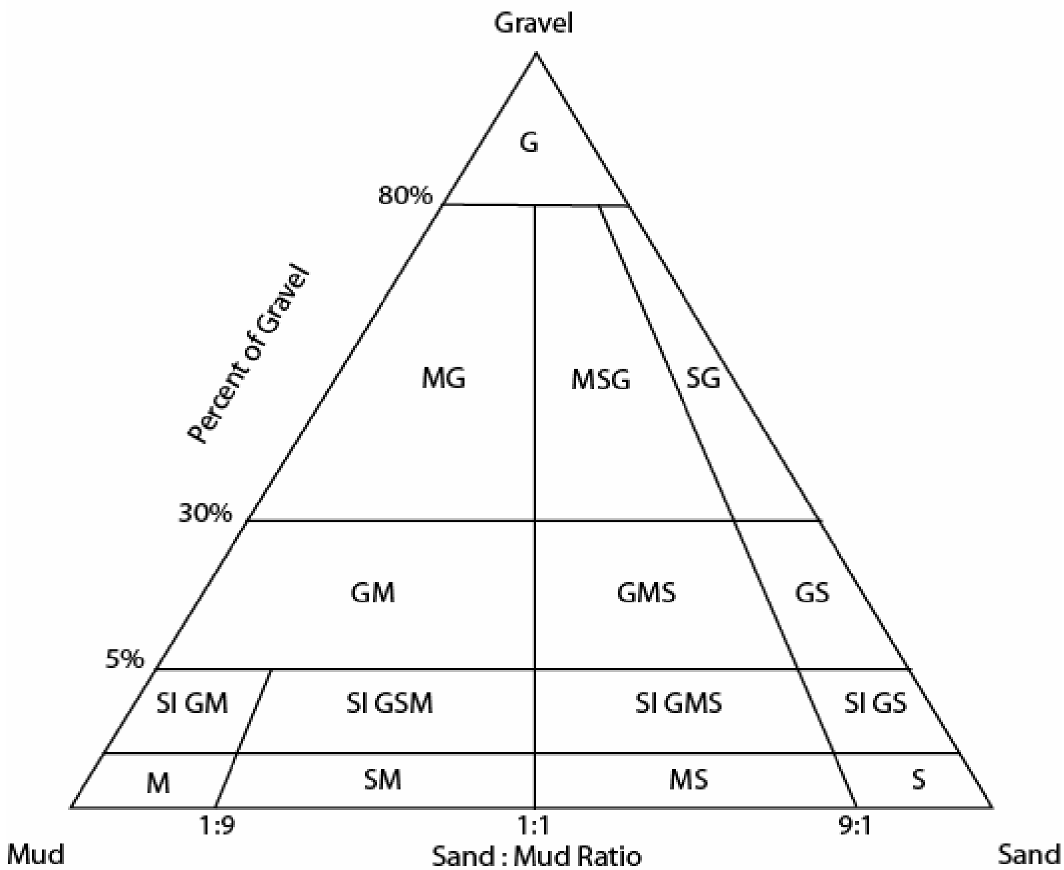
Author	Value of coefficient (C)	Porosity function φ(n)	Effective grain diameter (d_e) used in this research	Range of applicability
Hazen	$400 + 40((100n) - 26)$	$[1 + 10(n - 0.26)]$	$d_e = d_{10}$	0.1 mm < d_e < 3 mm $\eta<5$
Slichter	0.01	$n^{3.287}$	$d_e = d_{10}$	0.01 mm < d_e < 5 mm
Terzaghi	0.0061 or 0.0107	$\left[\frac{(n-0.13)}{(1-n)^{0.33}}\right]^2$	$d_e = d_{10}$	Coarse sand
Beyer	$0.0006\log\left(\frac{500}{\eta}\right)$	1	$d_e = d_{10}$	0.06 mm < d_e < 0.6 mm $1<\eta<20$
Sauerbrei	0.00375	$\frac{n^3}{(1-n)^2}$	$d_e = d_{10}$	Sand and sandy clay d<0.5 mm
Kozeny	0.0083	$\frac{n^3}{(1-n)^2}$	$d_e = d_{10}$	Coarse sand
$n = 0.255(1+0.83^{\eta}) =$ *porosity* $\quad \eta = \frac{d_{60}}{d_{10}} =$ *coefficient of uniformity*				

Sediment Classification Each sample was classified using nomenclature described by Folk (1954). This system divides samples into 15 textural groups based on the percent gravel and sand to mud ratio (Fig. 3.3). Permeability is in part a function of grain-size distribution and it follows that the permeability of each textural group is different.

A single facies in the Leona Formation may contain more than one of these textural groups. Variations in sediment texture often occur on the centimeter scale and they much more difficult to map on an outcrop scale than litho-facies.

3.2.4 Soil Permeability

The Leona aquifer is covered with soil in most places. The main source of recharge is through infiltration of precipitation through this soil. Field tests using a ring infiltrometer and a Guelph permeameter (constant head well permeameter) measured soil permeability. Descriptions of the most common soils are included in Section 2.1.1.



G :	Gravel
SG :	Sandy Gravel
MSG :	Muddy Sandy Gravel
MG :	Muddy Gravel
GS :	Gravelly Sand
GMS :	Gravelly Muddy Sand
GM :	Gravelly Mud
Sl GS :	Slightly Gravelly Sand
Sl GMS :	Slightly Gravelly Muddy Sand
Sl GSM :	Slightly Gravelly Sandy Mud
Sl GM :	Slightly Gravelly Mud
S :	Sand
MS :	Muddy Sand
SM :	Sandy Mud
M :	Mud

Figure 3.3. Sediment textural groups (modified from Folk, 1954).

A ring infiltrometer was used to measure the infiltration rate and field saturated hydraulic conductivity (K_{fs}) of the soil. The ring infiltrometer used was a steel cylinder with a radius of 30.5 cm (12 in.). The usual procedure for installing the cylinder is to push or drive it into the soil (ASTM, 2003c). This procedure was modified because the soil in the study area was very hard and dry, which prevented the cylinder from being driven into the soil without damaging the ring or disturbing the soil. A narrow trench was dug around the circumference of the cylinder and a small amount of water was poured in this trench to soften the soil. The cylinder was driven into this softened soil until the bottom edge was buried 10 to 15 cm (3.9 to 5.9 in.) below the surface. Moistened native soil was tamped into the trench around the cylinder. Water drawn from nearby water wells was ponded inside the cylinder to a depth between 8 and 14 cm (3.1 and 5.5 in.). A constant head was maintained with a graduated reservoir similar in concept to a mariotte bottle.

Reynolds et al. (2002) describe infiltration through a ring infiltrometer with the following relationship:

$$\frac{q_s}{K_{fc}} = \frac{Q}{\pi a^2 K_{fs}} = \frac{H}{C_1 d + C_2 a} + \frac{1}{\alpha * \left(C_1 d + C_2 a\right)} + 1 \qquad 3.3$$

where: q_s (L/T) is the near steady infiltration rate, Q (L^3/T) is the near steady flow rate, K_{fs} (L/T) is the field saturated hydraulic conductivity, a (L) is the radius of the ring infiltrometer, H (L) is the depth of ponded water, d (L) is the depth to which the ring is buried, $C_1 = 0.316\pi$ and $C_2 = 0.184\pi$ are constants that apply when $d \geq 3$ cm and $H \geq 5$ cm, and α^* is a soil macroscopic capillary length parameter. α^* equal to 0.12 is applicable for most agricultural soils. This equation describes three components of flow; flow due to hydrostatic pressure of the ponded water, flow due to the capillarity of unsaturated soil, and flow due to gravity. The first two components of flow cause water to flow laterally from the ring infiltrometer. Double ring infiltrometers are used to minimize lateral flow. These contain an outer ring which is intended to buffer the inner ring from lateral flow. Laboratory, field, and numerical simulation tests show that accuracy is only slightly improved by this method (Bouwer, 1986). Infiltration tests with the double ring method were not feasible in this study because the smaller inner ring could not be installed into the brittle and dry soil without disturbing the surface excessively.

Field saturated hydraulic conductivity (K_{fs}) was also measured with a Guelph permeameter (GP), which is a constant head well permeameter. K_{fs} is measured in an uncased well that is augered into the soil. A graduated Mariotte bottle was used to maintain a constant head of 5 cm or 10 cm (2.0 in. or 3.9 in.) in the well. This permeameter measures the steady-state recharge of water into the soil. An advantage of this method is that K_{fs} can be measured at different depths in the soil profile. GP measurements were collected at each ring infiltrometer site as well as others where large volumes of water were not available. One K_{fs}

measurement was collected between 28 cm (11.0 in.) and 60 cm (24.3 in.) and a second between 66 cm (26.0 in.) and 152 cm (59.8 in.). K_{fs} was calculated using the single head approach described by Reynolds and Elrick (2002). This method states that:

$$K_{fs} = \frac{CQ_s}{2\pi H^2 + C\pi a^2 + 2\pi H \alpha *^{-1}} \qquad 3.4$$

where Q_s (L^3/T) is the near steady flow of water into the soil, H (L) is the constant head of water in the well, a (L) is the radius of the well, α* (1/L) is a soil macroscopic capillary length parameter, and C is a dimensionless shape factor calculated by the following equation:

$$C = \left(\frac{H}{2.074a + 0.093H} \right)^{0.754} \quad \text{for } \alpha^* \geq 0.09 \text{ cm}^{-1}. \qquad 3.5$$

In this study, α* was assumed to be 0.12 cm^{-1}. According to Reynolds et al. (2002), α* equal to 0.12 is a suitable approximation for most agricultural soils.

3.3 Water Well Inventory and Water Level Measurements

Numerous wells have been completed in the Leona aquifer. Many of the wells are hand dug wells - some are more than 100 years old. Other wells are modern drilled wells. A survey was conducted to determine how many wells are in the area and how groundwater is used. Wells were located using the TWDB groundwater database, visual inspection from roadways, or by information from landowners. The initial goal of this survey was to obtain a complete inventory of all wells completed in the Leona aquifer in Caldwell County. A complete inventory proved to be difficult for several reasons. Some of the older wells have been plugged, caved in, or “lost” when surrounding buildings were abandoned or demolished. The TWDB database is not intended to be an exhaustive inventory and many wells were located in addition those included in the database. Some landowners were reluctant to provide information or access to wells especially those which supply household drinking water or contained pumps in the well. As a result this inventory may be biased toward hand dug wells to which some landowners assign less value. The following information was collected for each well included in the survey; well diameter, well depth, casing materials, depth to water from land surface, GPS location, and well use. GPS data were collected using a Garmin GPS III Plus GPS unit. Water level measurements were collected in June 2003 and again in November 2003. The water level in well #36 was measured weekly from May 31, 2003, to July 3, 2004, in order to observe changes at shorter time intervals. Sixty three wells were included in the first round of measurements and 40 wells in the second survey. Thirty nine wells were included in both surveys.

3.4 Stream Discharge Estimation

Stream discharge was estimated on July 17, 2004. Discharge was estimated by multiplying the cross sectional area of the stream by the flow velocity. The width and depth of the stream was measured with a tape measure. Surface velocity was calculated by timing a floating object over a known distance. Several surface velocity measurements were collected and the results were averaged. The surface velocity must be multiplied by a coefficient to approximate the average flow velocity of the stream. A coefficient of 0.85 was used as a general value (Dingman, 2002, p.612). Streamflow data for Plum Creek north of Lockhart was obtained from a USGS stream gaging station. The streamflow in all of the creeks, except Plum Creek, represent discharge from the Leona aquifer through springs and seeps. Plum Creek is fed by several tributaries as well as discharge from the Leona aquifer. The volume of discharge from seeps that do not flow into the major streams is unconstrained. There are many surface water bodies ranging in size from small reservoirs to stock tanks that collect discharge from these small springs and seeps.

3.5 Basic Water Chemistry and Nitrate Testing

Groundwater in the Leona aquifer is typically calcium bicarbonate facies water, frequently with high levels of nitrate (TWDB, 2005). Elevated nitrate levels are common in shallow alluvial aquifers such as the Leona aquifer. The most common sources of nitrate are leaching of ammonia type fertilizer from the soil, increased oxidation of soil organic nitrogen because of cultivation, livestock and domestic wastes from barnyards and septic tanks, or a combination of these sources. Ratios of stable nitrogen isotopes ($^{15}N/^{14}N$) have been used to determine the source of nitrates in the Leona aquifer near Lockhart, Texas (Kreitler, 1979) and in Medina County, Texas (Jones, 1996). Nitrate originating from non-fertilized cultivated fields has the smallest nitrogen isotope ratios, followed by nitrates from fertilized fields, and then livestock wastes. In the study by Kreitler (1979), groundwaters from wells located in cultivated fields were found to be contaminated by nitrate from cultivation and application of ammonia type fertilizer. Water collected from domestic wells showed contamination from livestock or domestic wastes. Domestic wells are often located near a barnyard or septic system. No groundwater samples from the Leona aquifer near Lockhart had $^{15}N/^{14}N$ ratios similar to the $^{15}N/^{14}N$ ratios of nitrogen fertilizer. This indicates that there is no direct leaching of fertilizer into the aquifer (Kreitler, 1979), although deep desiccation cracks in dry soil may provide a pathway for fertilizer to reach the aquifer.

Basic water chemistry data was collected in the field during the well survey and water level measurements. A MyronL Company Ultrameter was used to collect TDS, pH, and water temperature data. A ChemMetrics VVR multi-analyte photometer and nitrate VACU-vials were used to measure nitrate concentration. This kit was designed to produce the most accurate results when nitrate concentration is less than 70 ppm NO_3 as NO_3.

3.6 Construction of Numerical Groundwater Flow Model

A numerical model was developed to estimate aquifer scale hydraulic conductivity, flow paths, residence time, and recharge and discharge of groundwater. The computer code MODFLOW (Harbaugh et al., 2000) was used to create this model. MODFLOW uses a finite difference approximation to solve the groundwater flow equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}+W \qquad 3.6$$

where x, y, and z are coordinates which are parallel to the major axes of the flow system; $K_{xx,}$ $K_{yy,}$ and K_{zz} are hydraulic conductivity values in the x, y, and, z directions; h is hydraulic head; S_s is specific storage; t is time; and W is a volumetric flux per unit volume representing sources and/or sinks of water. W was used to represent recharge at the upper surface of the model, discharge at aquifer boundaries, and cross formational flow out of the surficial aquifer into the bedrock. The preconditioned conjugate gradient (PCG) package in MODFLOW was used to solve the flow equations. Convergence criteria for hydraulic head changes were set to 0.001 m (0.039 in) and for flow changes 11.6 l/sec (0.41 cfs).

MODPATH (Pollock, 1994) was used to model groundwater flow paths and to calculate residence time of water in the aquifer. MODPATH uses hydraulic head and flow data simulated in MODFLOW as well as user defined porosity. In these simulations, the porosity was defined as 20 percent, which is consistent for mixed sand and gravel sediments (Fetter, 1994, p. 86).

Construction of the numerical model included defining: the dimensions of the modeled aquifer, the finite difference grid of cells covering the aquifer, the structural framework of each cell, the hydrologic properties of each cell, the location and type of aquifer boundaries, and the units of measurement (meters and days). The structural information assigned to each cell included the elevation of the aquifer top and base. The hydrologic properties included were hydraulic conductivity and specific yield.

A single layer numerical model was constructed with a finite difference grid containing 25 columns and 62 rows (Fig. 3.4). Columns parallel the long axis of the aquifer and extend from the northwest to the southeast. Rows are parallel to the general strike of the land surface and water table. The dimensions of each grid cell are 300 m (984 ft) by 300 m (984 ft). The model only included cells within the boundaries of the aquifer, as seen on geologic maps (Barnes, 1974c), and all other cells were inactive. Cells on the perimeter of the aquifer were set as constant head cells. The hydraulic head in these cells is equal to the land surface elevation at the seepage face on the edge of the Leona terrace. The hydraulic head in the constant head cells was at least 1 m (3.3 ft) above the aquifer base to prevent complete drying of the cells.

The constant head cells simulate discharge from the perimeter of the aquifer. MODFLOW calculates the amount of water that is added or removed from these cells to maintain a constant head during a simulation. The remaining cells in the center of the model were designated as variable head cells, where hydraulic head was allowed to change during a simulation.

The northwest and southeast portions Leona aquifer were not included in the model to minimize the size of the model. The Leona aquifer thins northwest of the modeled area and few wells have been completed in that area. Consequently, little data were available for that portion of the aquifer. The northwest and southwest model boundaries cut across the mapped outcrop of the Leona aquifer. These areas were designated as variable head no flow boundaries. It was assumed that groundwater flow crossing those boundaries is small but hydraulic head still fluctuates in response to recharge. The Leona Formation is unsaturated in the area to the southeast that was omitted from the model. The Leona aquifer is saturated where it overlies relatively impermeable bedrock but the water table drops below the base of the Leona aquifer where it overlies more permeable Wilcox Group bedrock. The last six rows on the southeastern edge of the model correspond to an area where the Leona aquifer overlies the Wilcox Aquifer. This represents a transition from the partially saturated Leona aquifer to the unsaturated Leona aquifer.

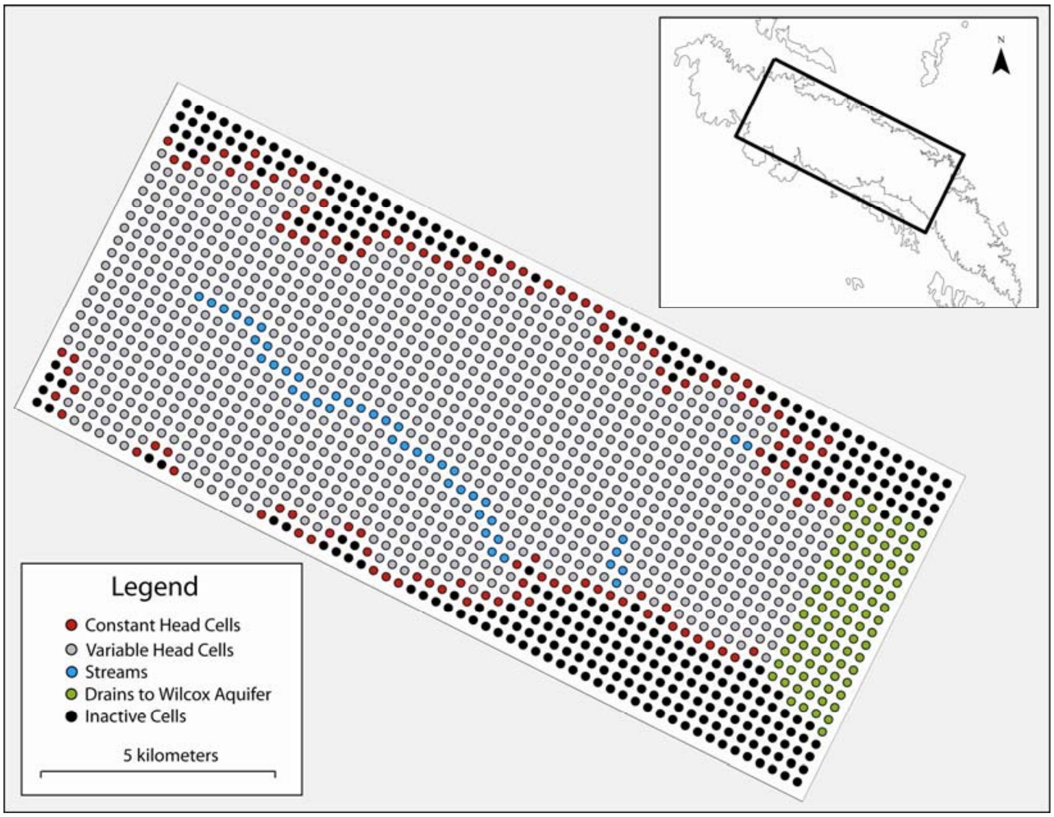


Figure 3.4. Layout for the numerical flow model of the Leona aquifer.

The top surface of the Leona Formation was based on 30 m DEMs obtained from Texas Natural Resources Information System digital data distribution system (USGS, 1999). The 30 m DEM was resampled as a 300 m DEM (Fig. 3.5) using ESRI ArcGIS 8.3. The base of the aquifer was modeled as an inclined plane generally parallel to the dip of the land surface. This plane intersects with the land surface and forms a line which approximates the outline of the Leona Formation seen on geologic maps (Barnes, 1974c). The modeled thickness of the Leona Formation averages 9.5 m (31.1 ft) and ranges from 2.0 m (6.7 ft) to 26.8 m (88.0 ft). The thickest area is found at Koegler Hill (Fig 3.5) found in the western portion of the model. The aquifer thickness was calculated as the land surface elevation minus the approximated aquifer base elevation and includes the soil horizon as part of the aquifer.

The RCH package in MODFLOW adds aerially distributed recharge to the groundwater flow equation. Precipitation was measured in a single location so recharge was assumed to be uniformly distributed across the model. Initial recharge estimates were based on precipitation data (NCDC, 2004) and water table fluctuation observed in well # 36, located on Figure A-1. The water table did not rise during periods when the monthly precipitation was less than 75 mm (3.0 in.), suggesting that this precipitation was lost to evapotranspiration or runoff. Modeled recharge was set to 0 mm/day during stress periods when monthly precipitation was less than 75 mm (3.0 in.). Recharge in other stress

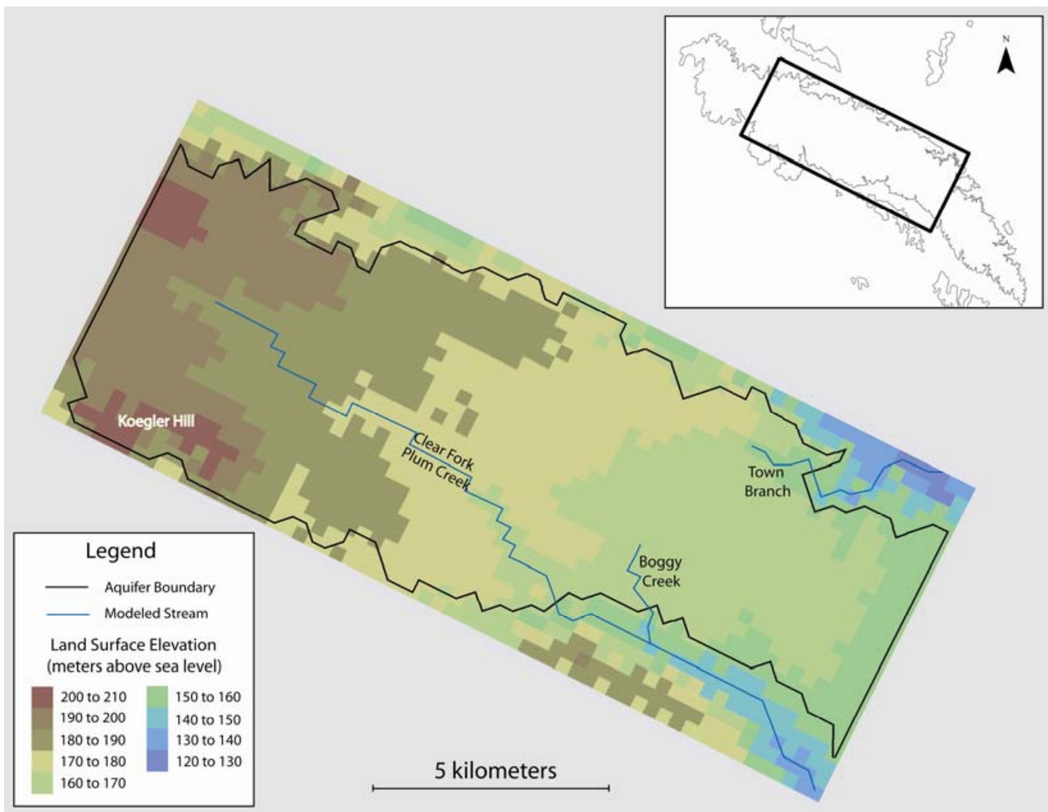


Figure 3.5. Digital elevation model representing the top of the Leona aquifer in the numerical model. Each grid cell is 300 m by 300 m (USGS, 1999).

periods was calculated as monthly precipitation minus 75 mm (3.0 in.). Recharge was adjusted by trial and error during periods dominated by water levels to match the measured well hydrograph.

The RIV package was used to simulate Clear Fork of Plum Creek, Boggy Creek, and Town Branch, which are significant sources of discharge. The streams were simulated with a gradient similar to the land surface, with the river bottom at least 1 m (3.3 ft) below the land surface. River stage was 1 m (3.3 ft) above the river bottom. The RIV package calculates groundwater flow to or from the stream based on hydraulic head in the aquifer and the conductance of the streambed. Streambed conductance is based on the thickness and hydraulic conductivity of the streambed material and the length and width of the stream reach. The streambed conductance was defined as 4,500 m^2/day (48,438 ft^2/day).

The permeable bedrock of the Wilcox Group was simulated using the DRN package in MODFLOW. The DRN package is similar to the RIV package, except that water can discharge from a given cell but cannot re-enter the aquifer through the drain. If the conductance of the drain is low, water can pool above the drain. Drains were placed in the last six rows of the model within the borders of the Leona aquifer. The drain elevation was set at the interface between the Leona Formation and the Wilcox Group. The drain conductance was defined as 200 m^2/day (2,153 ft^2/day). Groundwater flows from the Leona aquifer into the Wilcox aquifer. The water table often drops below the base of the Leona aquifer into the unconfined portion of the Wilcox aquifer.

The numerical model was calibrated with transient simulations because there was no sustained period with constant hydraulic head. The model was divided into 18 stress periods, each 30 days long. The model represents a period between January 2003 and June 2004. The process described below was completed several times with different values of hydraulic conductivity. Simulated changes in hydraulic head were compared to water level monitoring results obtained from well #36 (Fig. A-1). Hydraulic head declined between June 17, 2003 and September 7, 2003, which suggests that this is a no recharge period. This period was used for initial calibration since recharge was one variable which could be eliminated. Specific yield was adjusted by trial and error to match the simulated and measured rate of water level decline during this period. Increasing specific yield had the effect of slowing the rate of water level rise and fall. Once an appropriate specific yield was identified, recharge was adjusted in stress periods containing rising water levels. Hydraulic head was measured in 47 wells between May 2003 and June 2003. The simulated water table surface was compared to this data. Although the water table fluctuated seasonally, the measured water table was used as an approximation at all points in the transient model because the water table was not expected to change more than 1 m (3.3 ft). With a water table gradient of 0.23 percent, a vertical change of 1 m (3.3 ft) would move a water table contour 444 m (1,458 ft) laterally, or about one and a half grid cells. Three different variables (hydraulic conductivity, specific yield, and recharge) were adjusted during calibration and more than one combination of values produced a solution which matched the measured changes in hydraulic head. The final step was to verify that the values used for these variables made sense in this situation. For example, a recharge rate nearly equal to precipitation is not realistic because some of precipitation is lost to evapotranspiration, soil storage, and runoff.

A single value of hydraulic conductivity and specific yield were uniformly distributed throughout the model. It was assumed that the aquifer-scale hydraulic conductivity is dominated by the most permeable sediments in the Leona aquifer. Hydraulic conductivity was initially set as 270 m/day (879 ft/day) which is similar to measurements and estimates for the most permeable sediments. Hydraulic conductivity was lowered to 50 m/day in later simulations. This latter value is comparable to the effective hydraulic conductivity calculated later in Section 4.4.4. No specific yield data was available for the Leona aquifer. Specific yield was adjusted by trial and error from 0.04 to 0.35. The specific yield of gravelly sand typically ranges from 0.2 to 0.35 and the specific yield of clay ranges from 0 to 0.05 (Fetter, 1994, p. 91).

4: Results

Characterization of the Leona aquifer included identification and description of facies, monitoring of water levels over time, measurement and estimation of hydraulic conductivity, measurement of soil infiltration, estimation of stream discharge, analysis of basic chemistry (TDS, pH, temperature, and nitrate), and groundwater modeling. Following are the results of these observations and measurements.

4.1 Facies Descriptions.

The Leona Formation and the unconfined portion of the Wilcox Group were divided into seven different sedimentary facies based on grain lithology, grain size distribution, and sedimentary structures. Photographs were taken of typical examples of each facies (Fig. 4.1 and Fig. 4.2). The location of these photographs is shown in Figure 3.1.

4.1.1 Facies C: Clay

Facies C is tan or gray structureless clay (Fig. 4.1a) in discontinuous layers or small lenses. This facies is bounded by irregularly scoured top and bottom surfaces. The thickness of this facies ranges from a few centimeters to 40 cm (16 in.) and it is laterally continuous for less than 1 m (3.3 ft) up to 9 m (30 ft).

4.1.2 Facies LS: Limestone sand

This facies contains fine to very fine carbonate sand (Fig. 4.1b). This sand ranges from well to moderately sorted. This unit occurs in lenses up to 60 cm (24 in.) thick and may be laterally continuous for more than 35 m (115 ft). The base of this facies is erosional and may exhibit a broad lens shape or may be highly irregular. Small amounts of gravel are scattered within some lenses of this facies. Facies LS may be completely uncemented or well cemented. This facies may be massive or contain gently dipping cross stratification or fine horizontal laminations.

4.1.3 Facies HG: Horizontally bedded gravel

Facies HG contains gravel with varying amounts of sandy matrix. Some sediments of this facies contain little or no sand, and are open framework gravel. Other samples contain much more sand but are still clast supported. The sand is similar to the sand found in Facies LS. The open framework gravel and matrix-filled gravel create crude horizontal or nearly horizontal bedding (Fig. 4.2a). These beds form irregular lenses or discontinuous layers. Overall this facies is poorly sorted but with zones of well sorted sand or gravel. It ranges from well cemented to uncemented. The sandy portions are commonly the best cemented. The open framework gravel is often uncemented but it may also be cemented with a sparry calcite cement. This facies is up to 2 m (6.6 ft) thick.

4.1.4 Facies PlG: Planar cross-bedded gravel

Facies PlG contains poorly sorted planar cross-bedded gravel (Fig. 4.1c). In some samples, this unit consists only of sandy gravel. In other samples this facies may contain both open framework gravel and matrix-filled gravel as in Facies HG. Cross-beds grade from clean gravel to poorly sorted sand and gravel (Fig. 4.2b). The gravel tends to fine upward in each cross-bed. These cross-bed sequences are up to 10 cm (4 in.) thick. Cross-bedding can be very crude or well defined. The sandy gravel is well to moderately cemented and the clean gravel is poorly cemented.

4.1.5 Facies TG: Trough cross-bedded gravel

Facies TG contains trough cross-bedded poorly sorted gravel. Most individual trough cross-beds are tens of centimeters thick but some large cross-beds are more than a meter thick. This facies consists of many vertically and laterally stacked cross-beds. As a unit, this facies reaches 2 m (6.6 ft) thick and is laterally continouous for 25 m (82 ft). Some zones within this facies contain very well imbricated gravel. This facies is much less common than Facies HG and Facies PlG.

4.1.6 Facies MG: Massive gravel

Facies MG contains massive poorly sorted gravel and sand. This facies often contains very coarse gravel. This facies is usually less than 1 meter (3.3 ft) thick. Facies MG looks very similar to HG in poorer exposures.

4.1.7 Facies QS: Quartz sand

Facies QS is fine to medium, well-sorted quartz sand (Fig. 4.1d). This sand is uncemented. The full thickness of this facies was never exposed in outcrop, but it is at least 1 meter (3.3 ft) thick. The previous six facies are found within the Leona Formation. Facies QS is part of the Wilcox Group but it is hydrologically continuous with the Leona Formation. This facies is found below the Leona southeast of Lockhart, Texas. The Wilcox also contains shale layers but they were not observed in the outcrop (Weeks, 1930).

These seven facies were observed in several outcrops. Stratigraphic profiles describe the vertical stacking of these facies in the largest outcrops located in two gravel pits. These two gravel pits are located on the eastern edge of the Leona terrace about 7.7 km (4.8 mi.) apart shown on Fig. 3.1. Gravel pit HGP is north of gravel pit GGP. The vertical stratigraphy varies within the gravel pits. Two stratigraphic profiles were drawn in each gravel pit (Fig. 4.3). The two profiles designated as HGP East and HGP West are 80 m (260 ft) apart and the profiles designated as GGP North and GGP South, are only 9 m (30 ft) apart. All four represent a different distribution of facies. The distribution of facies was mapped on outcrop photos to describe the variability in two dimensions (Figures 4.4 and 4.5).

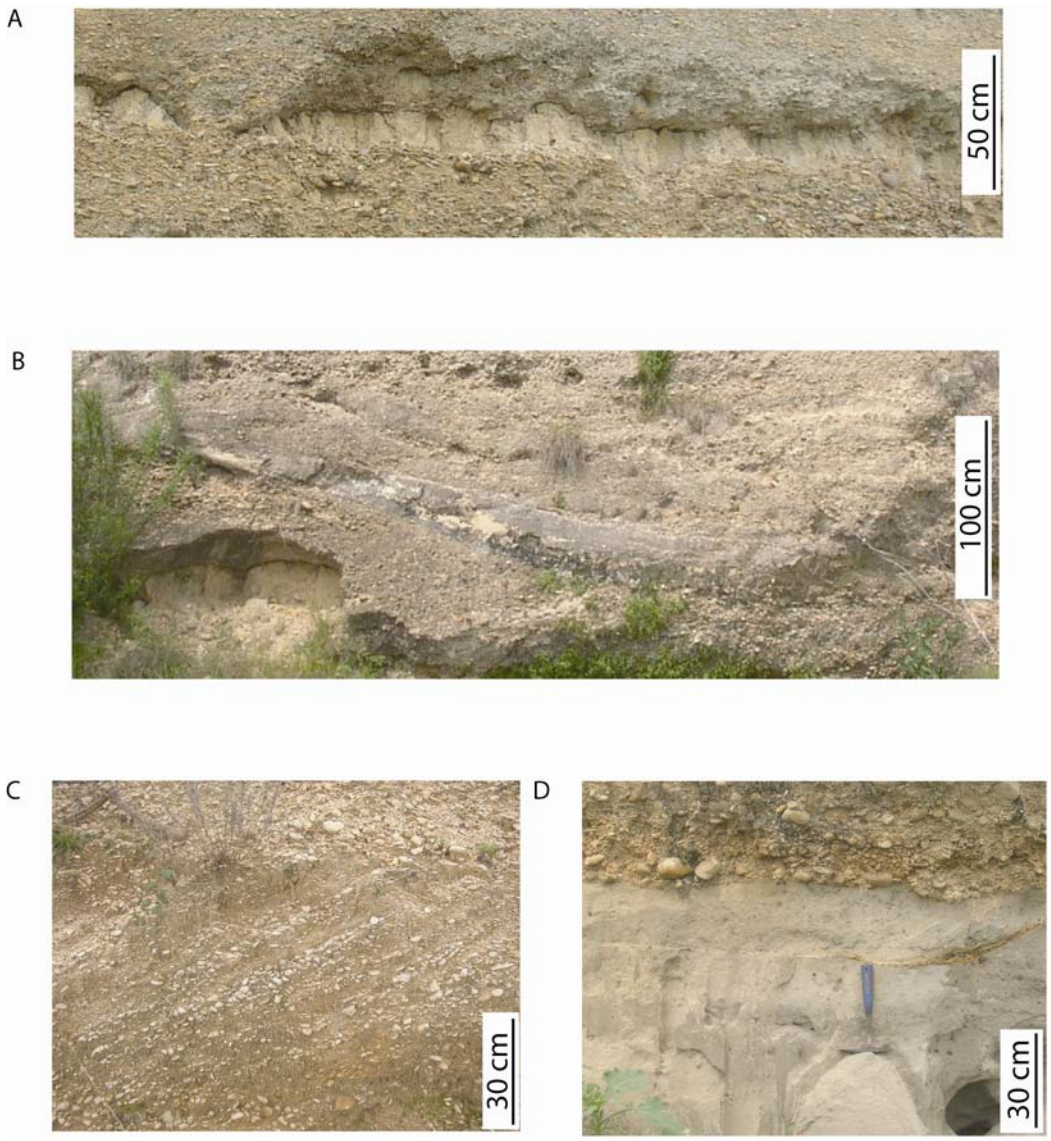


Figure 4.1. A. Irregular clay lens of facies C. B. Carbonate sand lens of facies LS. C. Planar crossbeds in facies PlG. D. Gravelly Leona Formation overlying the quartz sand of the Wilcox Group (facies QS).

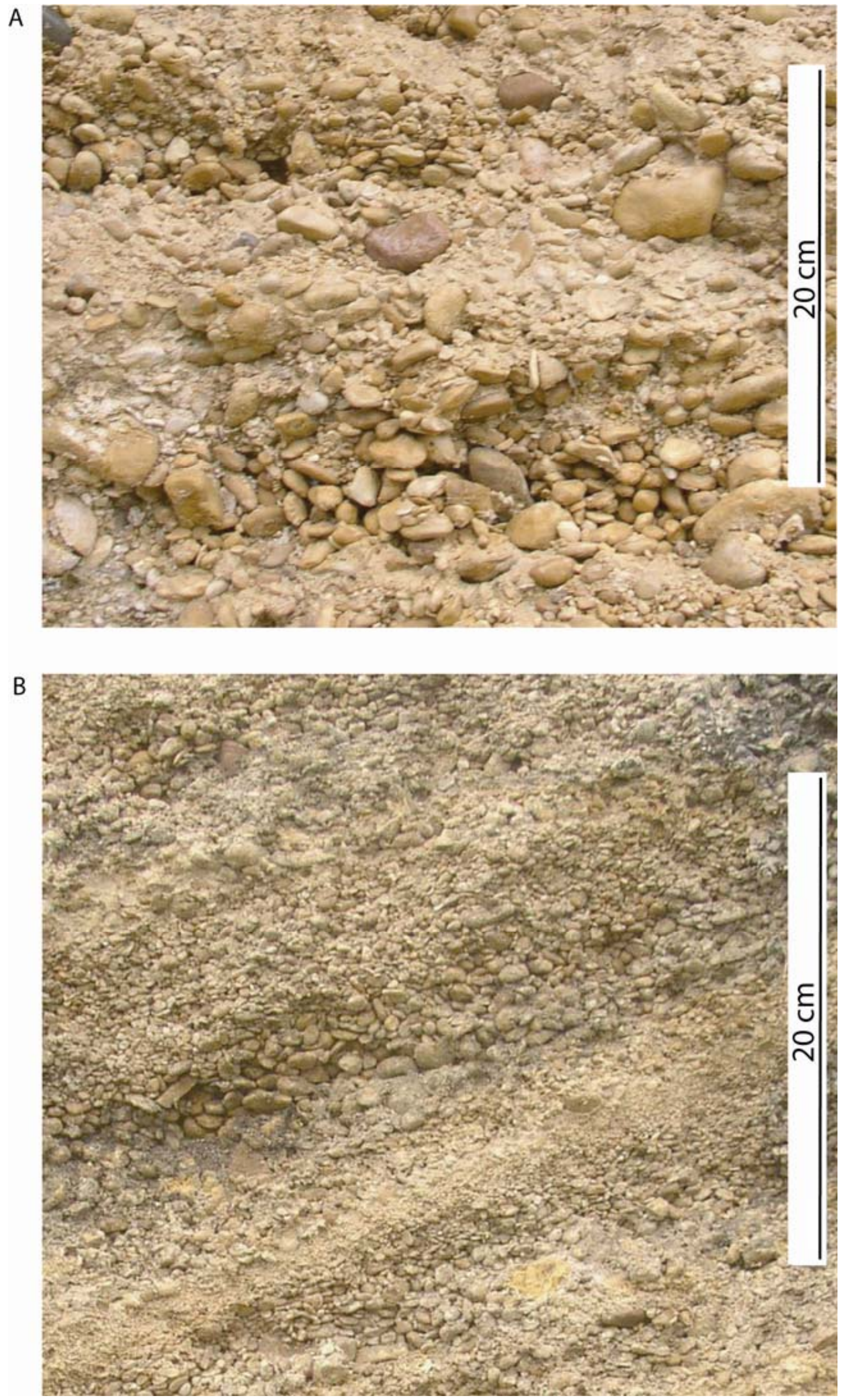


Figure 4.2. Interbedded layers of open framework gravel and sandy gravel occur in (A) facies HG and (B) facies PlG.

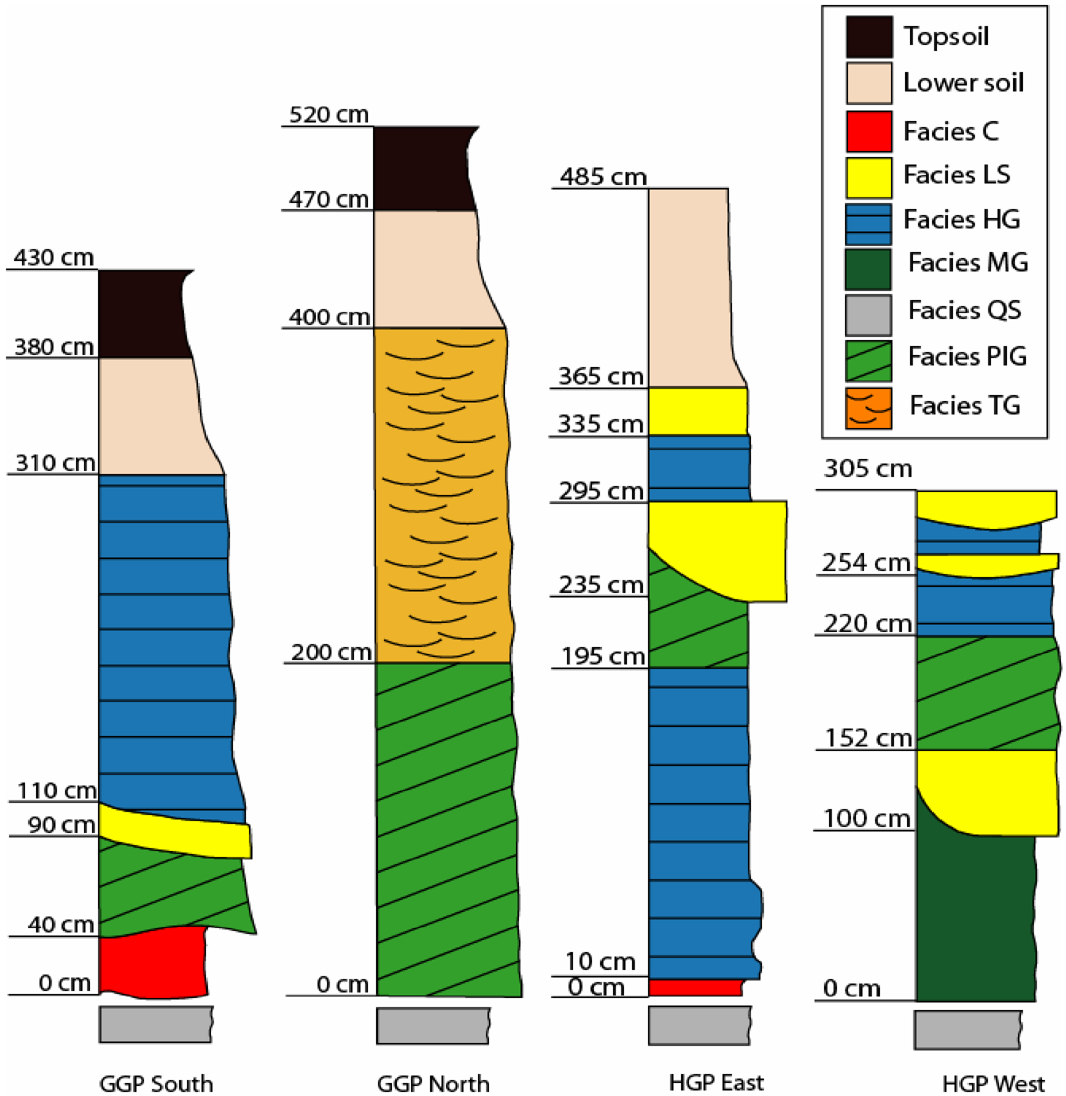


Figure 4.3. Stratigraphic profiles from the GGP gravel pit and the HGP gravel pit.

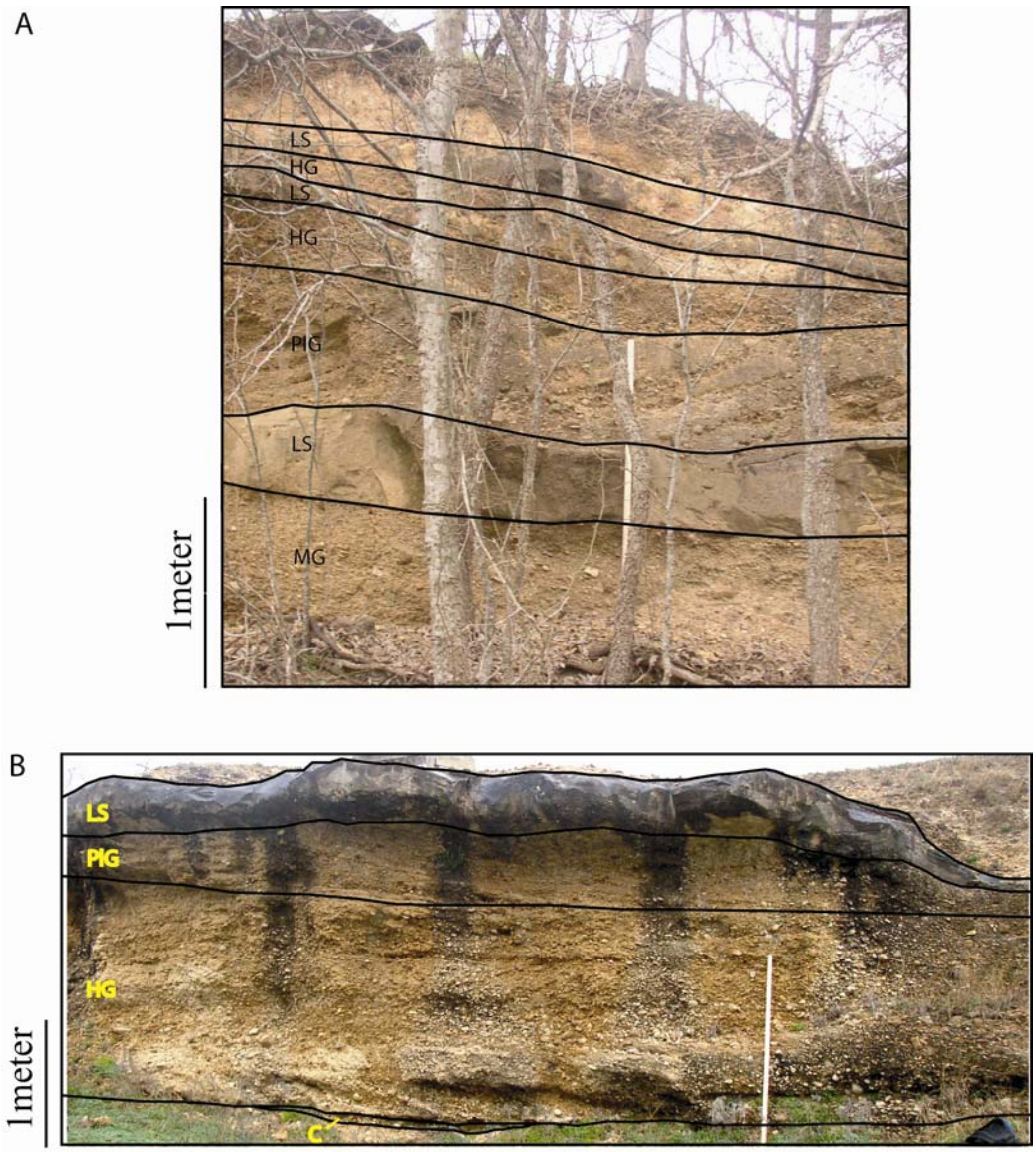


Figure 4.4. Facies distribution on the (A) HGP West outcrop
(B) HGP East outcrop.

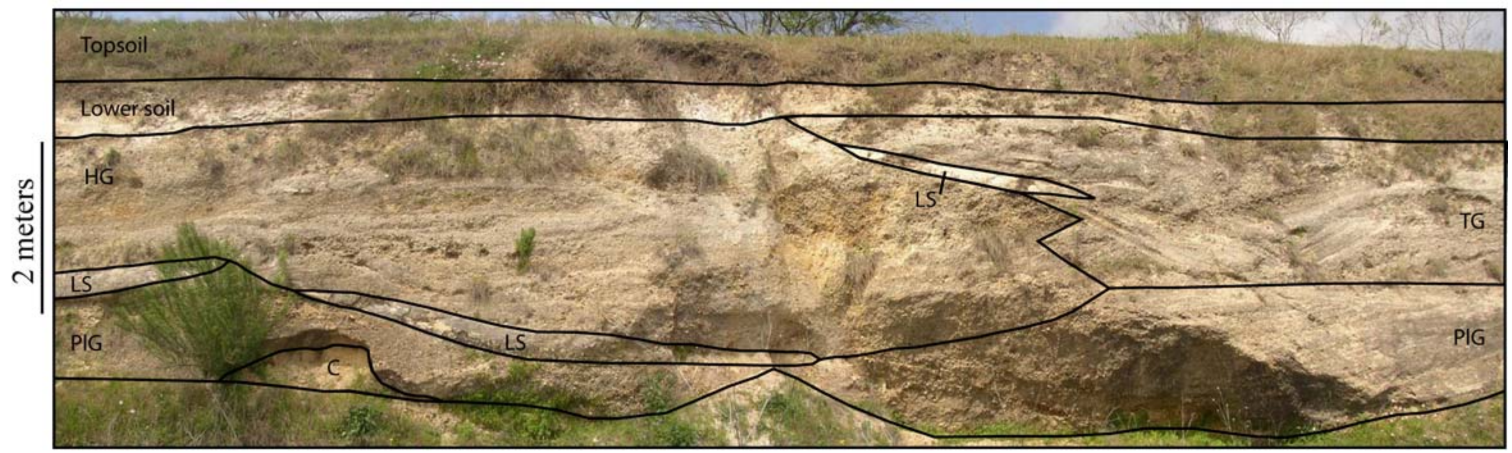


Figure 4.5. Facies distribution on the GGP South (left) and GGP North (right) outcrops.

4.2 Sediment Classification

The nomenclature described by Folk (1954) was used to divide 34 samples into sediment textural groups. These samples were collected from the Leona Formation except for three samples from the Wilcox Group and two samples from the A and C horizon of Lewisville series soil. The dominant types of sediment are pebble gravel (PG) and muddy sandy gravel (MSG). Other sediment types were gravelly muddy sand (GMS), muddy sand (MS), sand (S), sandy mud (SM), gravelly sand (GS), slightly gravelly sandy mud (SL GSM), slightly gravelly muddy sand (SL GMS), slightly gravelly mud (SL GM), and clay (C). Note that both of the clean sand samples belong to the Wilcox Group. Many of the litho-facies defined earlier include more than one of these sediment textures (Table 4.1).

4.3 Water Table Configuration and Seasonal Changes

The elevation of the water table was measured in June 2003 and November 2003. The water table mimics the land surface and groundwater flows toward the margins of the aquifer and to the southeast (Fig. 4.6). Local groundwater divides occur within the aquifer, although change in the hydraulic gradient is very gradual. The hydraulic gradient from the northwest edge of the aquifer to the southeast edge averages 0.27 percent meaning that the water table drops approximately 2.7 m in 1 km (14 ft in 1 mi.). The hydraulic gradient may be larger at the margins of the Leona aquifer but data were insufficient to prove this hypothesis.

Table 4.1. Textural groups represented in the different litho-facies of the Leona Formation, the Wilcox Group, and the overlying soil.

Litho-facies	Sediment Classification
C	SL GM, SM, and C
LS	GS, MS, and GMS
HG	PG and MSG
PlG	PG, MSG, and GMS
TG	PG
MG	PG and MSG
QS	S and MS
Topsoil (A horizon)	SM
Lower soil (C horizon)	SL GSM

One well (well #36) was measured on a weekly basis to observe short term changes in the water table (Fig. 4.7). Well 36 is located about 3.2 km (2 mi.) west of Lockhart (Fig. 4.6). This well was monitored between 5/31/03 and 7/3/04. The water level in the Leona aquifer is closely related to precipitation. A period of falling water table was observed between 6/14/03 and 11/6/03 when the water level dropped an average of 5 mm/day (0.19 in./day). The water table in other wells measured in June and again in November dropped an average of 4 mm/day (0.16 in./day). The water table fell at a faster rate of 6 mm/day (0.23

in./day) during a dry period between 7/17/03 and 8/11/03. The water table was highest in the spring and fell consistently until the end of the year, only rising during significant rainfall events or extended periods of rain. In the spring of 2004, several very wet periods caused the water table to rise in several rapid jumps. A series of storms caused the water table to jump 41 cm (16.2 in.) between 6/5/04 and 6/10/04.

Recharge to an aquifer is controlled by both the magnitude and duration of a single storm event and also by the frequency of precipitation events. To examine this, precipitation was totaled for the previous seven days. The water table only rose significantly when this seven day precipitation was 49 mm (1.94 in.) or greater. One exception occurred during a seven day period ending on 10/15/03 when 49 mm (1.92 in.) of rain fell without making significant changes to the water table. This period included a storm which dropped 37 mm (1.45 in.) in a single day. Much of this rainfall probably contributed to runoff rather than recharge.

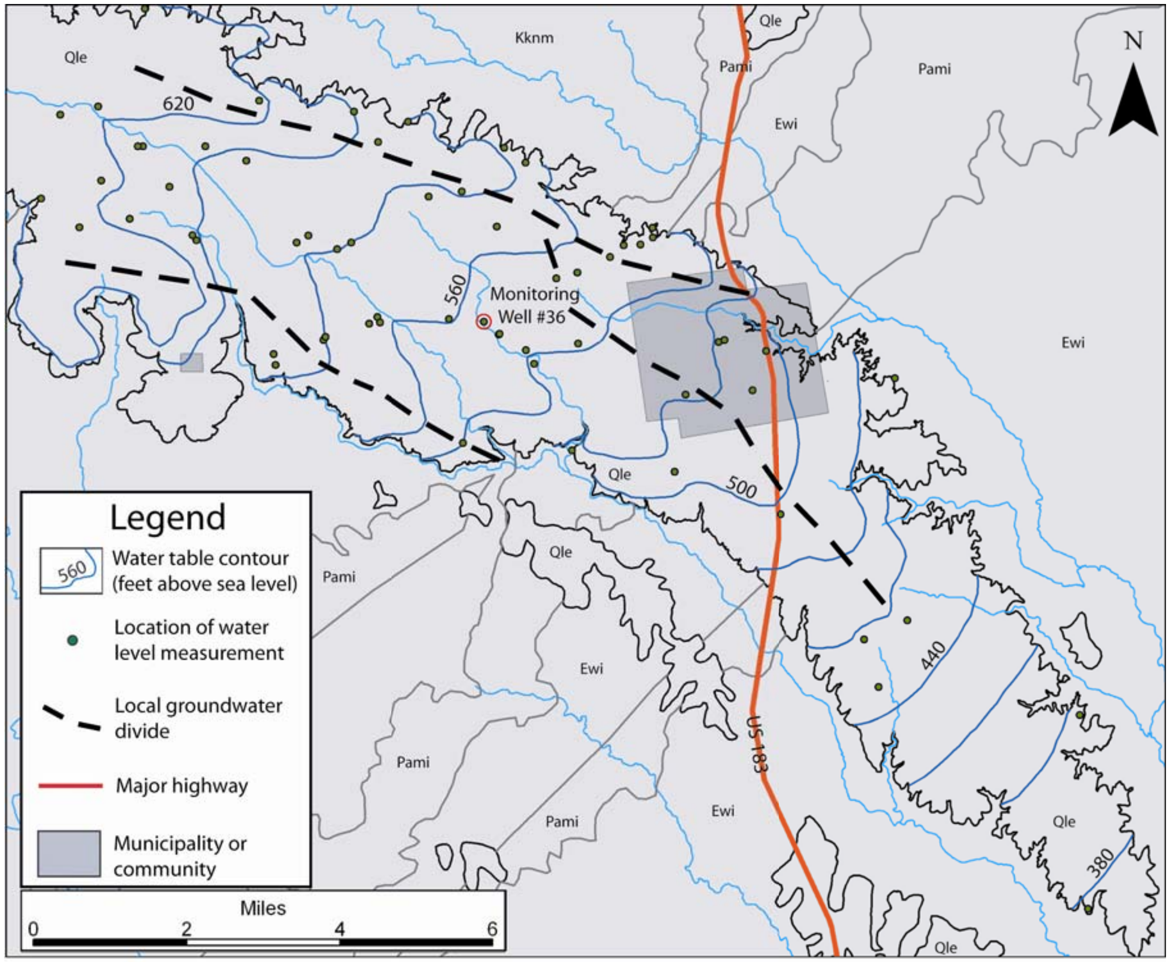


Figure 4.6. Water table in the Leona aquifer measured in June 2003 (geology modified from Barnes, 1974c).

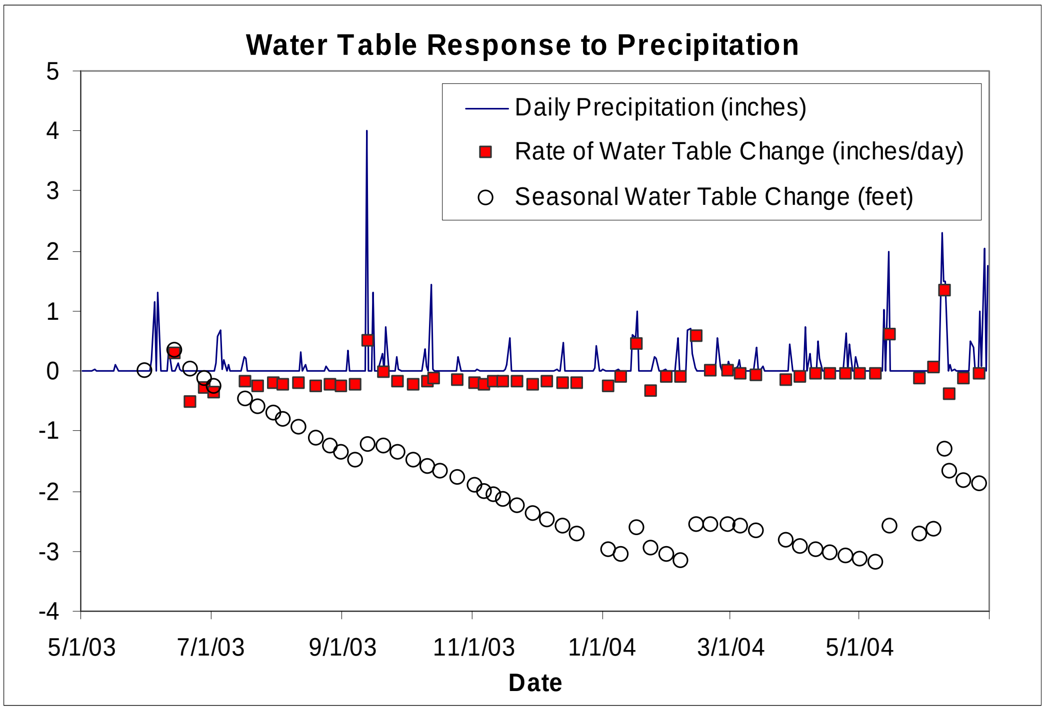


Figure 4.7. Seasonal water table fluctuation and response to precipitation observed in the Leona aquifer. During relatively dry periods the water table falls around 0.2 in. per day. The water table rises rapidly during large rainstorms (precipitation data from NCDC, 2004).

4.4 Hydraulic Conductivity

Hydraulic conductivity is an important variable in groundwater flow. Each of the facies described in Section 4.1 is expected to display a different range of hydraulic conductivity. The distribution of these facies varies from one outcrop to another as seen in Figure 4.4 and Figure 4.5. Hydraulic conductivity was estimated using empirical relationships between grain-size distribution and hydraulic conductivity and was also measured in the laboratory. The field saturated hydraulic conductivity of soil covering the Leona aquifer was obtained from infiltration tests using a ring infiltrometer and Guelph permeameter. Following are the results of these tests.

4.4.1 Hydraulic Conductivity Estimates from Grain Size Analyses

Hydraulic conductivities were estimated with grain size analyses of 32 samples. These estimates were developed to determine whether empirical relationships could provide reasonable estimates of K_{sat} for sediments found in the Leona and Wilcox aquifers. Empirical relationships formed by Hazen, Slichter, Terzaghi, Beyer, Kozeny, and Sauerbrei were used to estimate hydraulic conductivity. These six methods result in a range of estimates for each sample (Fig. 4.8). The maximum estimates of hydraulic conductivity for a single sample ranged from four times to 101 times larger than the minimum estimates.

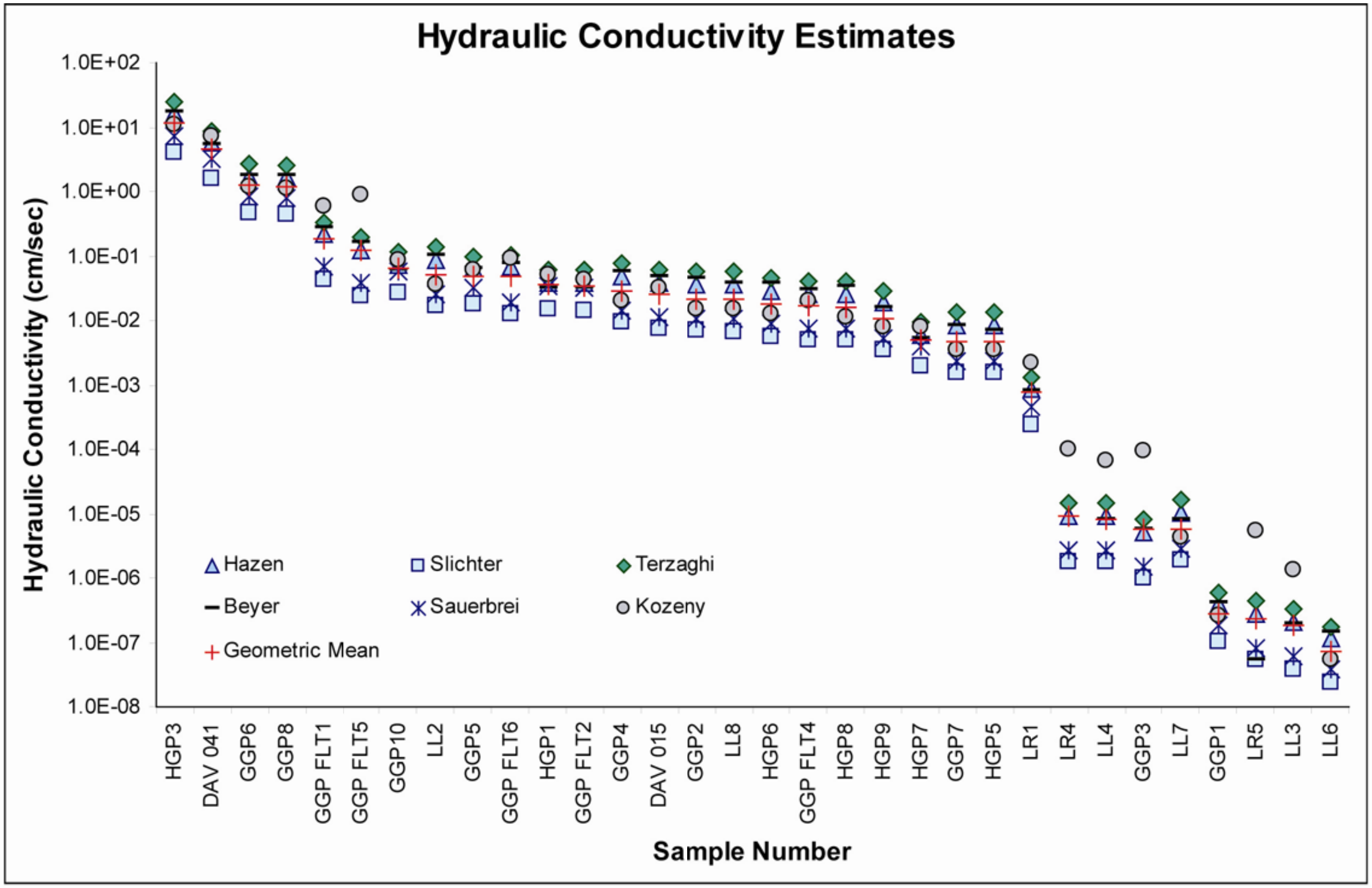


Figure 4.8. Estimated hydraulic conductivity of the Leona aquifer and the sandy portion of the Wilcox aquifer.

The average estimated hydraulic conductivity for each sample was calculated as the geometric mean of all six empirical methods (K_{GM}). This geometric mean was used for comparisons with measured values. K_{GM} ranged from 1.14×10^{1} cm/sec (32,319 ft/day) to 7.29×10^{-8} cm/sec (2.1×10^{-4} ft/day) (Fig. 4.8).

4.4.2 Disturbed Sample Hydraulic Conductivity Tests

The hydraulic conductivity of three disturbed samples (DAV 041, GGP FLT1, and DAV 015) was measured with the constant head permeameter. Their hydraulic conductivities were 5.8 cm/sec (16,443 ft/day), 2.28 cm/sec (6,464 ft/day), and 0.12 cm/sec (340 ft/day). The measured values of these samples were 1.3, 12.7, and 4.7 times the geometric mean of hydraulic conductivity estimates (Fig. 4.9). Higher than expected measured values suggest that the packing of sediment into the permeameter did not represent *in situ* conditions. The samples may have been more densely packed in the field. The two most permeable samples belonged to the pebble gravel textural group and the third was muddy sandy gravel (Table 4.2).

4.4.3 Undisturbed Sample Hydraulic Conductivity Tests

The hydraulic conductivity of eight undisturbed samples (GGP FLT5, HGP1, GGP FLT2, GGP FLT6, GGP FLT4, HGP7, LR1, and LL7) was measured with the constant head or falling head permeameter. Their hydraulic conductivities ranged from 2.8×10^{-2} cm/sec (79 ft/day) to 4.0×10^{-4} cm/sec (1 ft/day). The measured conductivities of two of these samples were 2.8 and 71.0

times the geometric mean of hydraulic conductivity estimates. The measured values of the other six samples ranged from 0.0 to 0.8 times the geometric mean of hydraulic conductivity estimates (Fig. 4.9). Coarser textured sediment tended to be more permeable than finer textured sediment (Table 4.2). The measured hydraulic conductivities of the undisturbed samples were less than the measured hydraulic conductivities of the disturbed samples, even for samples in the same textural group.

4.4.4 Outcrop Scale Permeability

The four stratigraphic profiles discussed in Section 4.1 described the distribution of hydraulic conductivity and the effective horizontal hydraulic conductivity (K_{eff}) of a vertical segment of the aquifer. Each facies was assigned a uniform hydraulic conductivity based on measured values and empirical estimates. Measured hydraulic conductivity was used if samples were collected from the described unit. Empirical estimates of hydraulic conductivity were used if no laboratory measurements were collected. If no samples were collected, the hydraulic conductivity was based on the geometric mean of the empirical estimates and measurements collected from the same facies in other areas. The effective hydraulic conductivity (K_{eff}) at each stratigraphic profile was calculated as the area-weighted arithmetic mean of hydraulic conductivity along each profile (Fig. 4.3), excluding the overlying soil. K_{eff} was calculated in order to compare the overall hydraulic conductivity of the Leona aquifer at different locations.

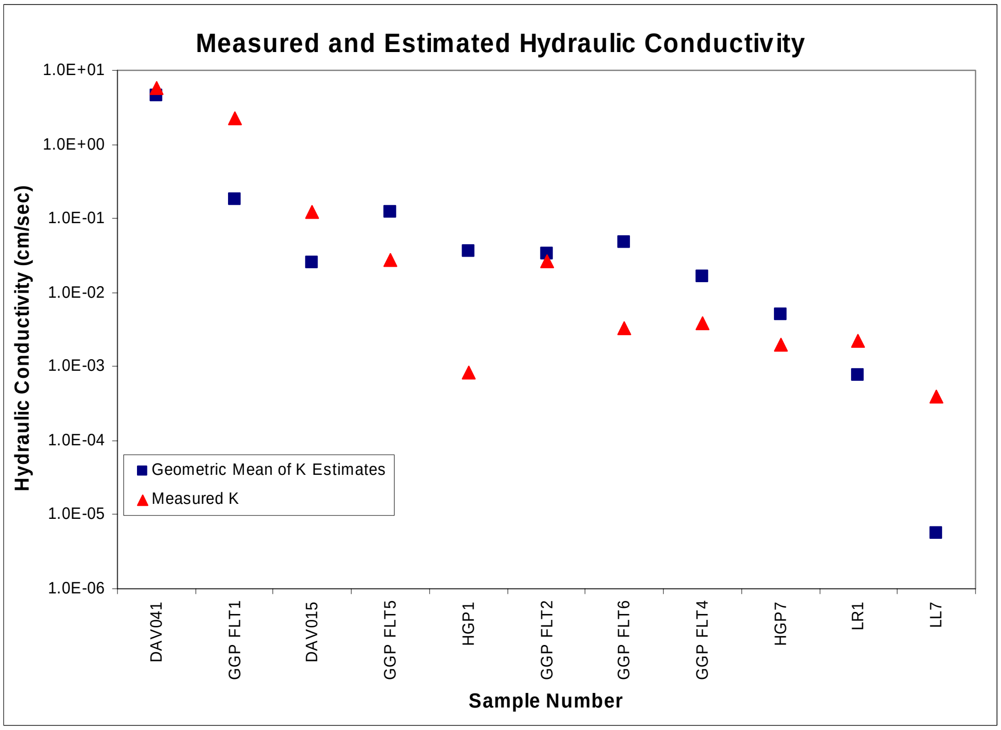


Figure 4.9. Comparison of laboratory measurements and empirical measurements of hydraulic conductivity. The first three samples are disturbed samples and the rest are undisturbed samples.

Table 4.2. Comparison of laboratory measurements and empirical estimates of hydraulic conductivity. Laboratory samples include disturbed samples (DS) and undisturbed samples (US).

Sample ID	Sample Type	Textural Group	Measured K (cm/sec)	Geometric Mean of K Estimates (cm/sec)
DAV 041	DS-1	PG	5.8×10^{0}	4.6×10^{0}
GGP FLT1	DS-2	PG	2.3×10^{0}	1.8×10^{-1}
DAV 015	DS-3	MSG	1.2×10^{-1}	2.6×10^{-2}
GGP FLT5	US-1	PG	2.8×10^{-2}	1.2×10^{-1}
GGP FLT2	US-2	GS	2.6×10^{-2}	3.4×10^{-2}
GGP FLT4	US-3	MSG	3.8×10^{-3}	1.7×10^{-2}
GGP FLT6	US-4	PG	3.3×10^{-3}	4.8×10^{-2}
LR1	US-5	MS	2.2×10^{-3}	7.8×10^{-4}
HGP7	US-6	MS	2.0×10^{-3}	5.1×10^{-3}
HGP1	US-7	S	8.4×10^{-4}	3.6×10^{-2}
LL7	US-8	GMS	4.0×10^{-4}	5.6×10^{-6}

Table 4.3. Mean hydraulic conductivity (cm/sec) of stratigraphic profiles through the Leona aquifer.

K (cm/sec)	HGP East	HGP West	GGP North	GGP South
Arithmetic mean (K_{eff})	3.5×10^{-2}	1.4×10^{-2}	1.3×10^{-1}	1.9×10^{-2}
Geometric mean	9.3×10^{-3}	5.9×10^{-3}	3.4×10^{-2}	1.3×10^{-3}
Harmonic mean	5.7×10^{-6}	2.1×10^{-3}	9.4×10^{-3}	1.4×10^{-6}

K_{eff} at the HGP East profile and HGP West profile was 3.5×10^{-2} cm/sec (99 ft/day) and 1.4×10^{-2} cm/sec (40 ft/day), respectively. The K_{eff} at the GGP North profile and GGP South profile was 1.3×10^{-1} cm/sec (369 ft/day) and 1.9×10^{-2} cm/sec (54 ft/day), respectively. The geometric and harmonic means of hydraulic conductivity along each stratigraphic profile result in different values and are shown in Table 4.3.

The facies distribution mapped on outcrop photographs is useful for describing the lateral distribution of hydraulic conductivity in the Leona aquifer. Facies were mapped on outcrops represented by stratigraphic profiles HGP West, HGP East, GGP North, and GGP South. The mapped area of the HGP West outcrop covered 10.2 m^2 (110 ft^2). A 12.5 cm (5 in.) by 12.5 cm grid was drawn on the outcrop photograph in order to estimate the area. The mapped area of the HGP East outcrop covered 21.6 m^2 (233 ft^2). The upper portion of the HGP East stratigraphic profile is not visible on the photograph (Fig. 4.4b). Given the larger scale of the outcrop, a 25 cm (9.8 in.) by 25 cm grid was drawn on the outcrop to estimate the area. The mapped area containing the GGP North and GGP South profiles covered 53.8 m^2 (579 ft^2), excluding the soil layers. The area was estimated with a 25 cm (9.8 in.) by 25 cm grid drawn on the outcrop photograph. The vertical columns of the grid drawn on the outcrop photos approximate a series of stratigraphic profiles. The effective hydraulic conductivity (K_{eff}) in each column was calculated with the method discussed earlier in this section for the measured stratigraphic profiles. K_{eff} for each column represents a bulk hydraulic conductivity through the described thickness of the Leona aquifer. Lateral variations in hydraulic conductivity can be examined with a series of effective hydraulic conductivity values (Fig. 4.10). K_{eff} at the HGP West outcrop ranged laterally from 1.3×10^{-2} cm/sec (37 ft/day) to 1.6×10^{-2} cm/sec (45 ft/day). K_{eff} at the HGP East outcrop ranged laterally from 4.0×10^{-2} cm/sec (113 ft/day) to 5.5×10^{-2} cm/sec (156 ft/day). K_{eff} at the GGP North and GGP South outcrops ranged laterally from 2.1×10^{-2} cm/sec (60 ft/day) to 1.4×10^{-1} cm/sec (397 ft/day). The two outcrops in the HGP gravel pit display less variation in K_{eff} than the outcrops in the GGP gravel pit (Fig. 4.10).

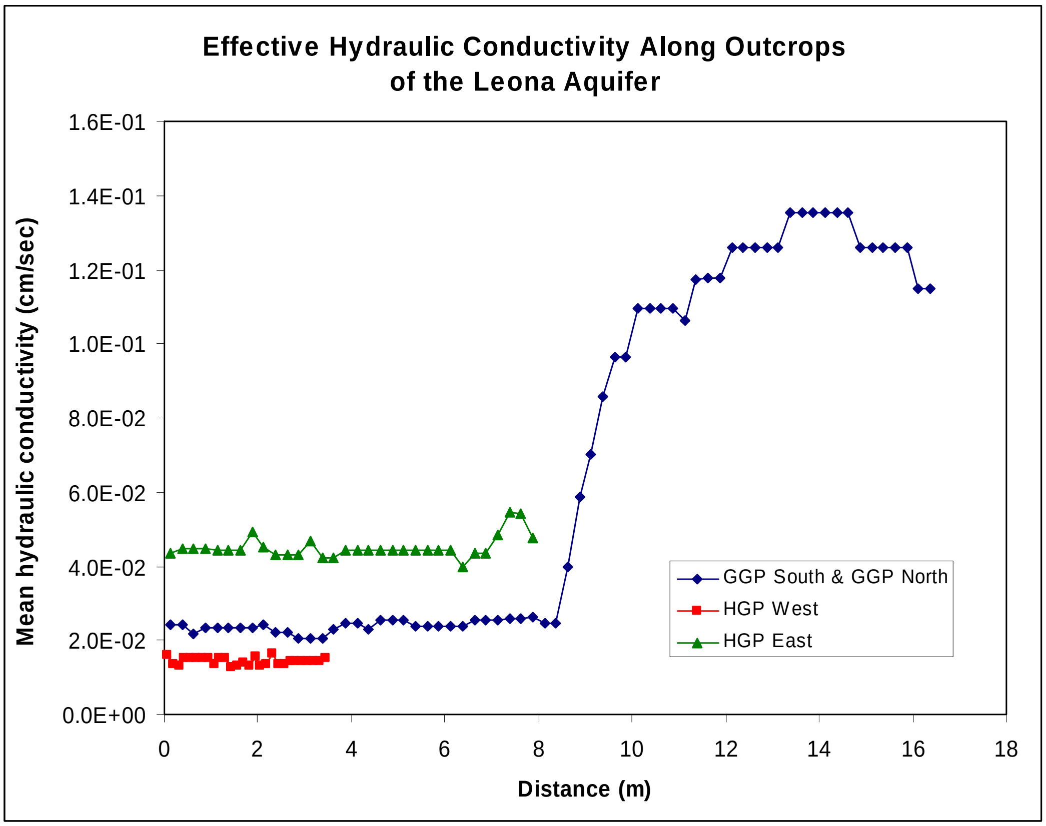


Figure 4.10. Lateral variation in effective hydraulic conductivity (K_{eff}) of vertical segments of the Leona aquifer. The GGP and HGP West outcrops trend from the south to the north and the HGP East outcrop trends from the west to the east.

4.5 Soil Permeability

Six infiltration tests were completed in soil covering the Leona Formation using a ring infiltrometer. Four of the tests measured infiltration in Branyon type A soils and two in Branyon type B soils. Three tests were located in short-grass pastureland and three were located in cultivated cropland. Branyon A soils were the most permeable with a mean K_{fs} value of 6.4×10^{-5} cm/sec (0.18 ft/day). The mean K_{fs} of Branyon B soils was 1.3×10^{-5} cm/sec (0.037 ft/day). The soil in cultivated fields was only slightly more permeable than soil in pastures. The mean K_{fs} values were 4.8×10^{-5} cm/sec (0.136 ft/day) and 4.6×10^{-5} cm/sec (0.130 ft/day) respectively. A statistically more significant number of samples is necessary to determine if true correlations exist between K_{fs}, soil type, and land use. Table 4.4 shows the range of K_{fs} observed in the soil covering the Leona aquifer.

Table 4.4. K_{fs} observed in the soil covering the Leona aquifer. K_{fs} is calculated from infiltration rate which was measured with a ring infiltrometer.

	Soil Type		Land Use	
	BrA	BrB	Cultivated Field	Pasture
Mean K_{fs} (cm/sec)	6.4×10^{-5}	1.3×10^{-5}	4.8×10^{-5}	4.6×10^{-5}
Maximum K_{fs} (cm/sec)	8.7×10^{-5}	1.6×10^{-5}	7.3×10^{-5}	8.7×10^{-5}
Minimum K_{fs} (cm/sec)	3.6×10^{-5}	9.9×10^{-6}	9.9×10^{-6}	1.6×10^{-5}
Number of Measurements	4	2	3	3

A total of 15 Guelph permeameter (GP) measurements were collected at nine different locations. Queeny C soils were the most permeable with a mean K_{fs} of 3.9×10^{-4} cm/sec (1.11 ft/day) and Branyon A soils are the least permeable with a mean K_{fs} of 7.8×10^{-5} cm/sec (0.22 ft/day). The GP tests indicate that Branyon B soils are more permeable than Branyon A soils which is contradictory to data from the ring infiltrometer tests. A statistically more significant number of measurements are necessary to determine if there is a correlation between soil type and K_{fs}. Soils in cultivated fields have a mean Kfs of 8.0×10^{-5} cm/sec (0.23 ft/day) and soils in pastures have a mean K_{fs} of 1.8×10^{-4} cm/sec (0.51 ft/day). These numbers are biased because there are no cultivated fields located on Queeny C soils and Queeny C soils are the most permeable. Table 4.5 shows the range of K_{fs} observed in each soil type and land use.

The GP tests resulted in a greater range of K_{fs} than the ring infiltration tests (Fig. 4.11). Test location WP1 is found in a short grass pasture containing BrB type soil. The K_{fs} from the ring infiltration test was more than one order of magnitude less than K_{fs} from GP measurements. Test location HF1 is located in a cultivated field containing Branyon A type soil. The K_{fs} from the ring infiltration test at HF1 was an order of magnitude greater than K_{fs} from GP measurements. Cultivating the soil may increase the permeability of the soil near the surface. In other locations the results from the ring infiltration tests and GP tests were similar. The GP tests at locations GF and GrP2 showed significantly more

Table 4.5. Range of K_{fs} measured is soils covering the Leona aquifer using a Guelph permeameter.

	Soil Type			Land Use	
	BrA	BrB	QuC	Cultivated Field	Pasture
Mean K_{fs} (cm/sec)	7.8×10^{-5}	1.8×10^{-4}	3.9×10^{-4}	8.0×10^{-5}	1.8×10^{-4}
Maximum K_{fs} (cm/sec)	2.5×10^{-4}	4.6×10^{-4}	4.1×10^{-4}	2.5×10^{-4}	4.6×10^{-4}
Minimum K_{fs} (cm/sec)	6.7×10^{-6}	6.3×10^{-6}	3.7×10^{-4}	6.3×10^{-6}	1.6×10^{-5}
Number of Measurements	8	5	2	4	11

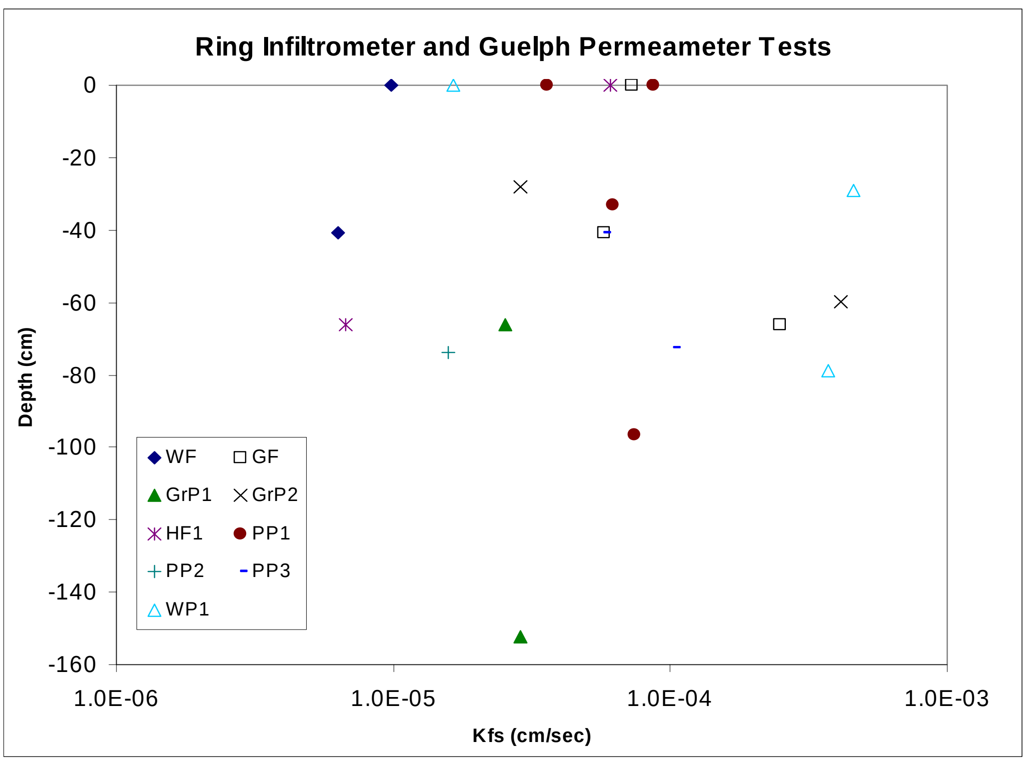


Figure 4.11. Results of ring infiltrometer and Guelph permeameter tests. Symbols represent different test locations. Ring infiltrometer data are plotted at zero depth.

permeable soil at greater depths. GF is located in a cultivated field with Branyon A type soil and GrP2 is located in a brushy pasture containing Queeny C soil. The lower GP test at GrP2 was within the gravelly portion of the soil profile.

4.6 Stream Discharge Estimates

Stream discharge (Q) was estimated on July 17, 2004 (Fig. 4.12). Streamflow data for Plum Creek north of Lockhart was obtained from a USGS stream gaging station and estimates for several other streams were made using the method described in Section 3.4. The streamflow in all of the creeks, except Plum Creek, represents discharge from the Leona aquifer through springs and seeps. The stream discharge in Plum Creek near the community of Uhland was 71 l/sec (2.5 cfs) and 11 km (6.8 mi.) downstream, north of Lockhart, the stream discharge was 249 l/sec (8.8 cfs). Streamflow increases because Plum Creek is fed by several tributaries as well as discharge from the Leona aquifer through numerous unmeasured springs and seeps. On the outcrop of the Leona aquifer, the streams with the greatest discharge were Clear Fork Plum Creek, 212 l/sec (7.5 cfs); Dry Branch, 193 l/sec (6.8 cfs); Town Branch, 85 l/sec (3.0 cfs); and Boggy Creek, 34 l/sec (1.2 cfs). The estimate for Dry Branch was made downstream of a small surface water reservoir which may influence the rate of discharge.

No streams with discharge greater than 9 l/sec (0.3 cfs) were observed where the Leona aquifer covers the permeable Wilcox Group. This is significant because groundwater flows to the southeast towards the Wilcox aquifer. The lack of discharge at the down-gradient end of the Leona aquifer suggests that groundwater infiltrates into the Wilcox aquifer.

4.7 Basic chemistry and nitrate

In the first round of sampling, the mean TDS of groundwater samples (TDS = 538 ppm) was greater than surface water samples (TDS = 404 ppm). Mean pH was lower in groundwater samples (pH = 7.2) than surface water samples (pH = 7.7). The mean temperature of groundwater samples (T = 24.4 ºC) was lower than surface water samples (T = 27.7 ºC). Figure 4.13 describes the ranges observed in TDS, pH, and temperature.

In the second round of sampling, the mean TDS was again greater in groundwater samples (TDS = 633 ppm) than surface water samples (TDS = 475 ppm). The concentration of TDS was higher in the fall for both groundwater and surface water samples. Mean pH was lower in groundwater samples (pH = 7.3) than surface water samples (pH = 7.6). The mean temperature of groundwater (T = 20.3 ºC) was higher than surface water (T = 18.2 ºC). The change in surface water temperature from June to November reflects seasonal differences in air temperature. Figure 4.13 gives the ranges observed in TDS, pH, and temperature. Nitrate was also measured during the second round of sampling. Measurements were collected in 23 wells and 5 streams. The concentration of nitrate in groundwater ranged from 3.5 ppm NO_3 to greater than the instrument range of 70.0 ppm NO_3 with a median concentration of 48.5 ppm NO_3. The concentration of nitrate in surface water ranged from 3.5 ppm to 41 ppm with a mean concentration of 25.2 ppm. The highest concentration of nitrate is in the center of the aquifer (Fig. 4.14).

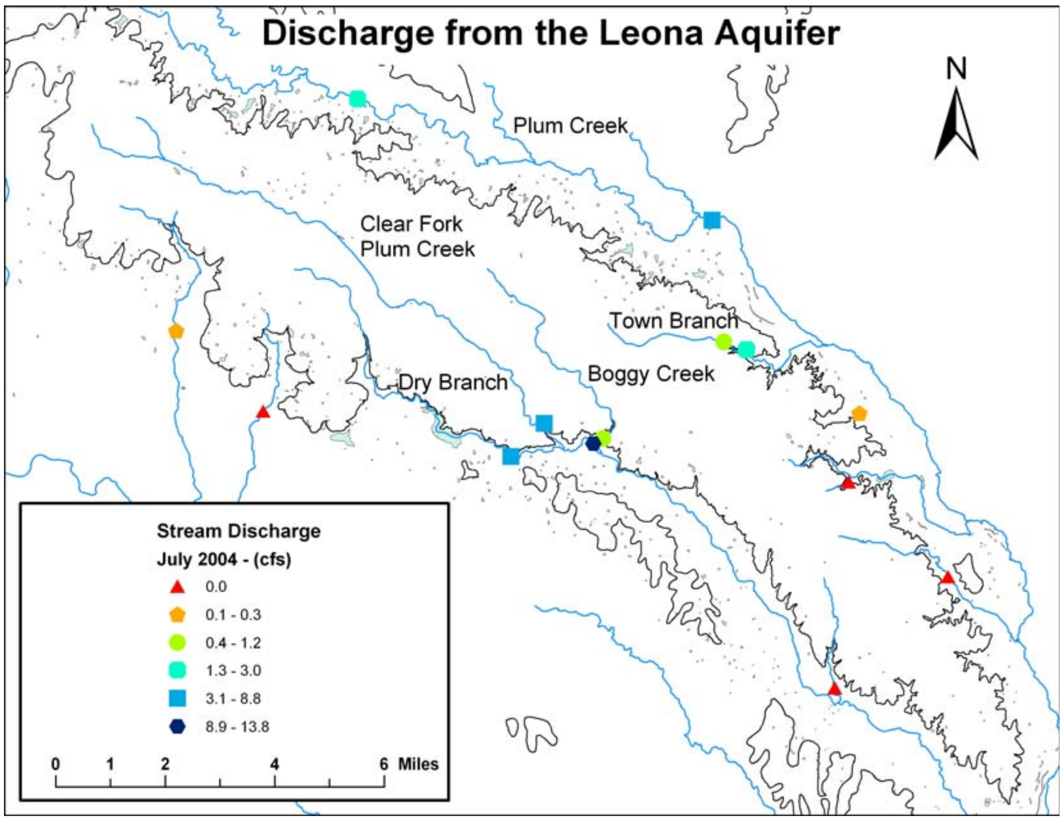


Figure 4.12. Estimated stream discharge on July 17, 2004.

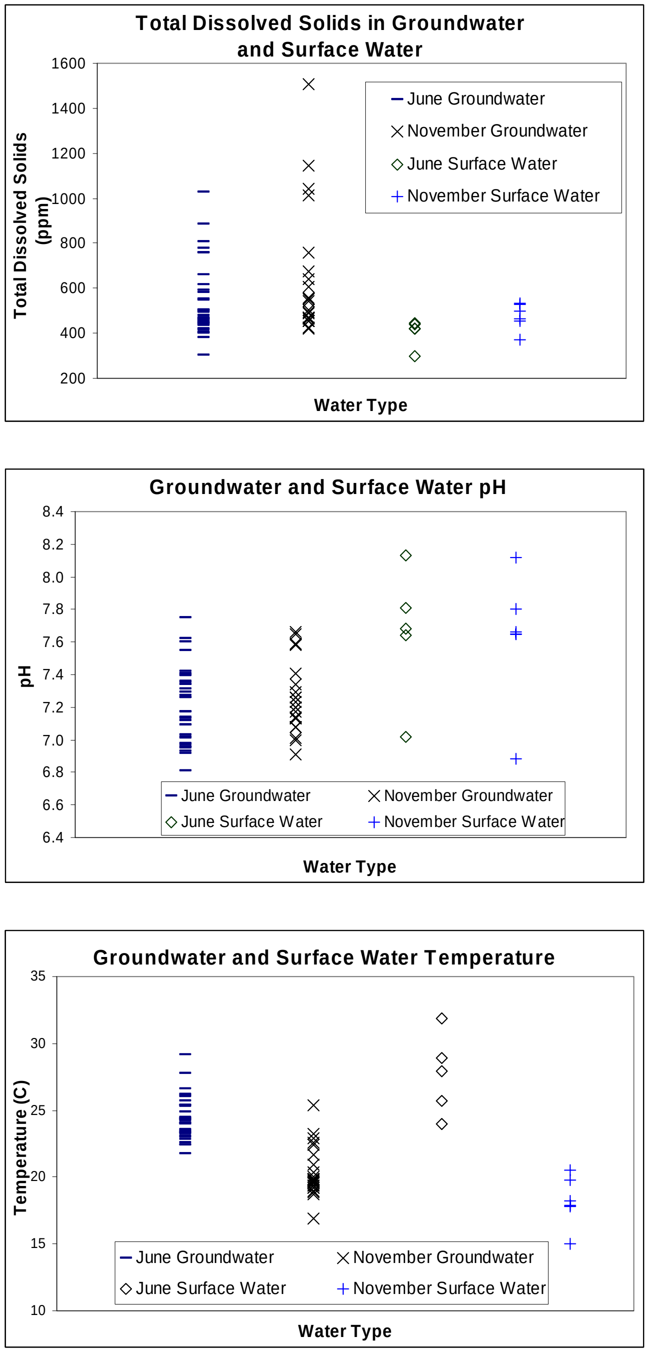


Figure 4.13. Total dissolved solids, pH, and temperature of surface water and groundwater. Measurements were collected in June 2003 and November 2003.

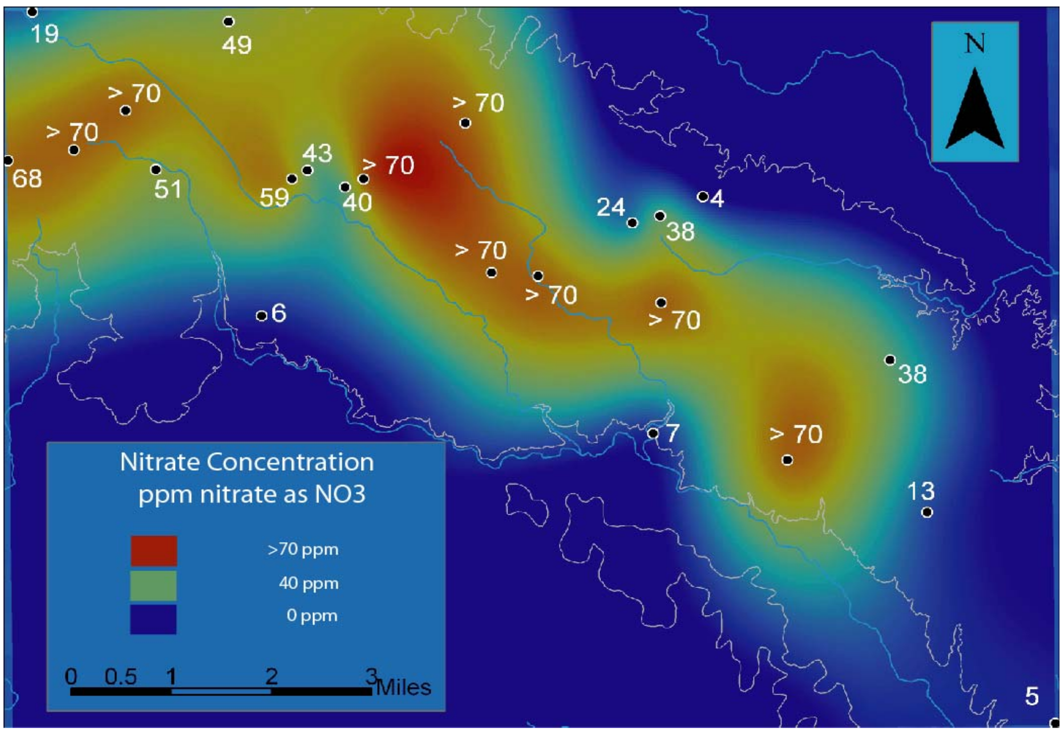


Figure 4.14. Spatial distribution of nitrate in the Leona aquifer. The background surface is a spline interpolation of the data points in black.

4.8 Numerical model

Groundwater flow in the Leona aquifer was simulated with a numerical model constructed with MODFLOW. The aquifer was represented as a single layer unconfined aquifer. The model was divided into 18 transient stress periods, each 30 days long.

In simulation 1, hydraulic conductivity was set to 270 m/day (886 ft/day). This value falls in the range of the most permeable samples collected from gravel pits. Specific yield was adjusted by trial and error until the water table fell at a rate similar to that observed between June 17, 2003 and September 7, 2003. The best match was found with a specific yield of 0.3. The water table response was not large enough during periods of recharge. Recharge was increased in each stress period dominated by a rising water table on the well hydrograph. Nearly 100 percent of precipitation was needed to match the well hydrograph. This is not reasonable because some precipitation is lost through evapotranspiration, soil storage, and runoff.

The same procedure was followed for simulation 2, where hydraulic conductivity was decreased to 50 m/day (0.06 cm/sec) (164 ft/day). This hydraulic conductivity is similar to the effective hydraulic conductivity (K_{eff}) calculated earlier in Section 4.4.4 with stratigraphic profiles and facies maps of gravel pit outcrops. A specific yield of 0.04 produced the best match of periods dominated by falling water levels. This value of specific yield is lower than typically assumed for sand and gravel aquifers. Recharge was adjusted to match periods dominated by rising hydraulic head. Modeled recharge in 2003 was 5 percent of annual precipitation and recharge in the first half of 2004 was 13 percent of precipitation.

In simulation 3, hydraulic conductivity was held at 50 m/day (164 ft/day) and evapotranspiration (ET) was added at a constant rate of 0.6 mm/day (0.024 in/day). The ET extinction depth was set at 1 meter, meaning that ET occurred only when the water table was within one meter of the land surface. Adding ET allowed the modeled water table to decline at a faster rate without lowering specific yield. The best match of periods dominated by falling water levels was given when Sy = 0.1. Long term changes in the simulated well hydrograph (Fig. 4.15) match those in the measured hydrograph. The simulated water table surface does not reproduce all of the complexities but generally represents the measured water table surface (Fig. 4.16). In this simulation, modeled recharge in 2003 was 9 percent of annual precipitation and recharge in the first half of 2004 was 20 percent of precipitation. The larger amount of recharge in 2004 is a result of higher than normal precipitation. The measured precipitation in the first six months of 2004 was 623 mm (24.5 in.) which is nearly equal to the total annual precipitation in 2003, [629 mm (24.8 in.)].

The numerical model was better at simulating the rate and duration of water table change than simulating the water table elevation. The performance of the model was evaluated with relative change in water levels. This is the fluctuation in the water table relative to the first measured value and the equivalent simulated value. Figure 4.15 compares simulated fluctuation to measured fluctuation. In Simulation 2, the root mean squared (RMS) error for the measured and simulated water table elevation was 2.2 m (7.2 ft) and RMS error for measured and simulated trends in water table fluctuation was 0.26 m (0.85 ft). In Simulation 3, the root mean squared (RMS) error for the measured and simulated water table elevation was 2.5 m (8.2 ft) and RMS error for measured and simulated trends in water table fluctuation was 0.05 m (0.16 ft).

Given the available data, there was not a unique combination of parameters that allowed the model to match the measured hydraulic head. Simulation 3 was the simulation containing the most realistic parameter values based on a gravelly sand aquifer. Field measurements of specific yield would eliminate a variable that was adjusted in the model.

Five hypothetical wells were placed in the final model in order to evaluate the effects of pumping on the aquifer. Pumping tests were run for a period of 61 days. Recharge was 0 mm/day and evapotranspiration was 0.6 mm/day (0.024 in/day). During this period the water table dropped due to natural discharge from the aquifer. This natural drawdown ranged from 0.3 m (1.0 ft) to 0.5 m (1.6 ft) at the location of the simulated wells. In the first pumping simulation, each well was pumped at a rate of 0.04 l/sec (0.6 gpm).

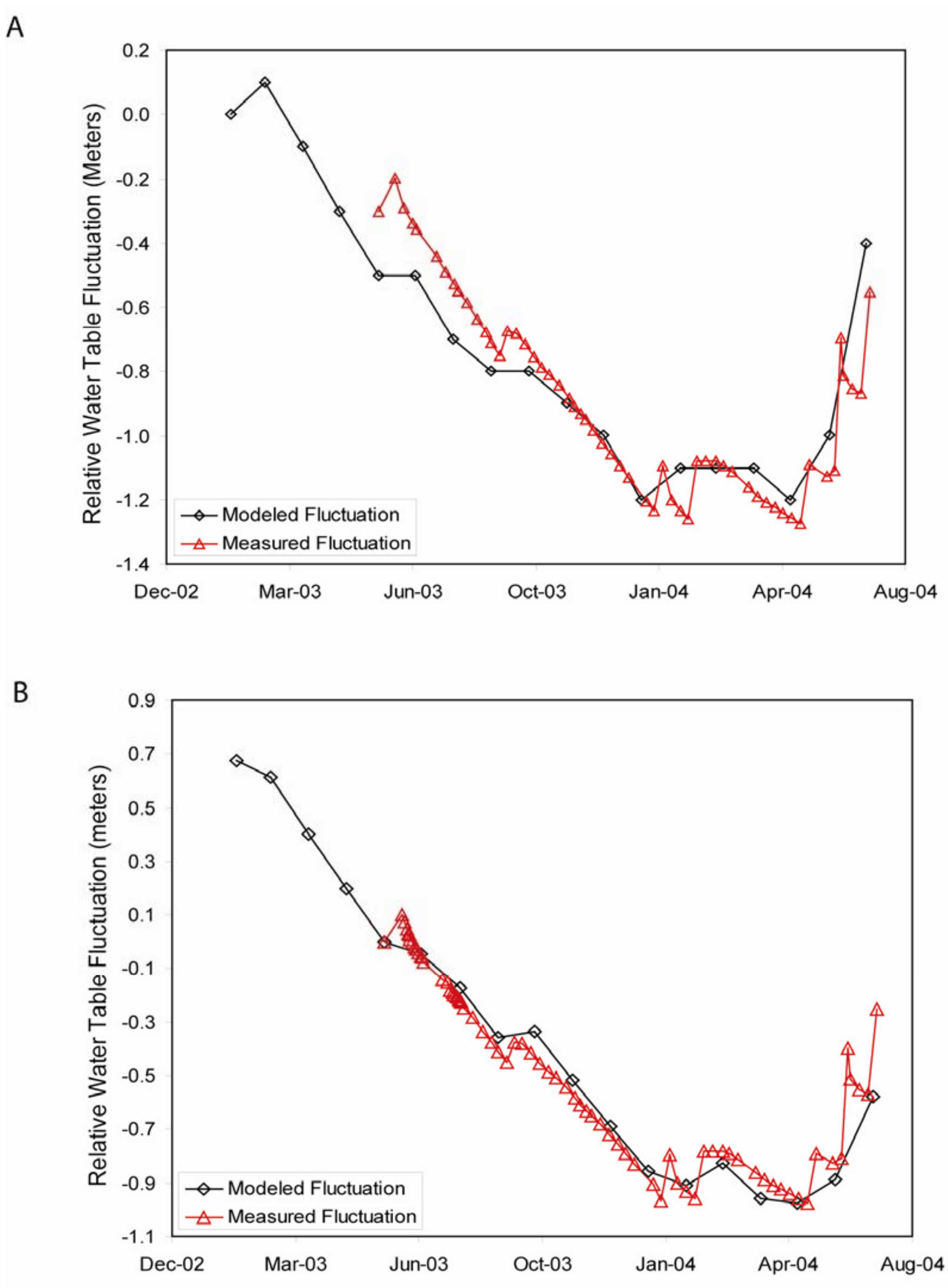


Figure 4.15. Relative water table fluctuation in (A) Simulation 2; and (B) Simulation 3; compared to measured fluctuation.

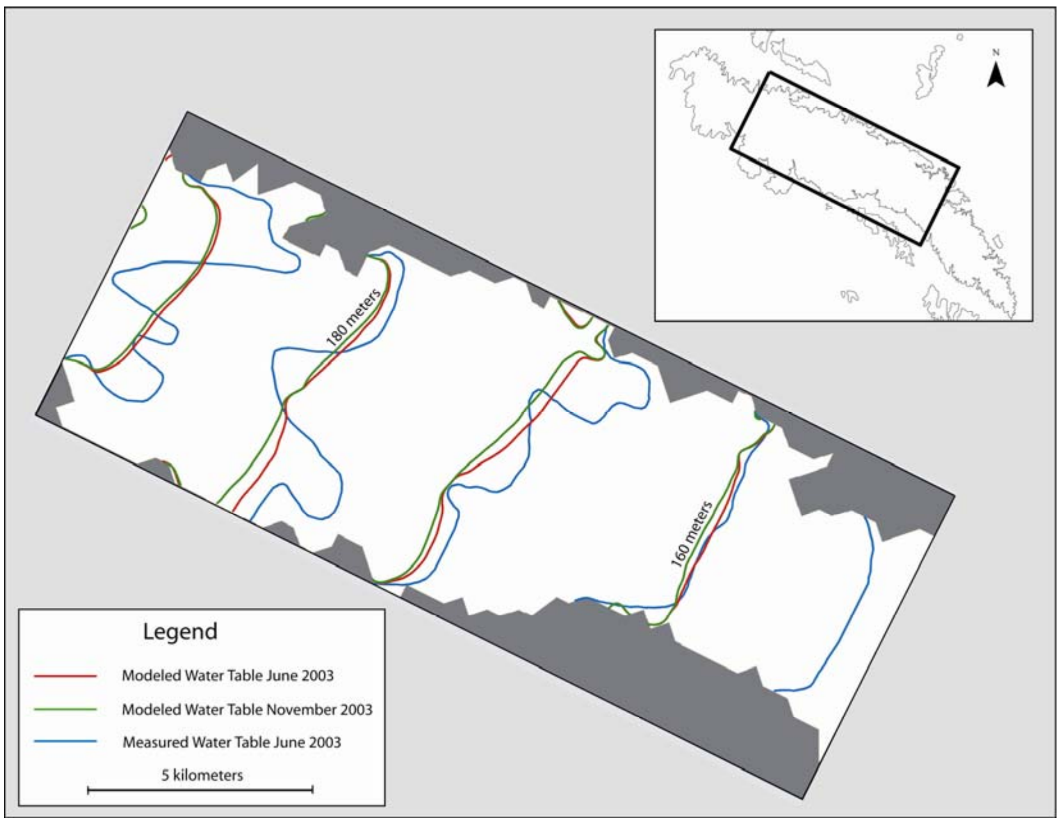


Figure 4.16. Numerical simulations of the water table in the Leona aquifer.

The drawdown at the wells was very small, ranging from 3 mm (0.12 in.) to 6 mm (0.24 in.) (Fig. 4.17). During the second pumping simulation, the pumping rate was increased to 3.5 l/sec (55 gpm). The drawdown at the wells was larger, ranging from 0.3 m (1 ft) to 0.6 m (2 ft) (Fig. 4.17). This is equal to or 1.5 times larger than the water level decline due to natural discharge with out pumping. The cones of depression during this pumping test extended 900 m (2,953 ft) to 1,200 m (3937 ft) away from the well.

MODPATH was used to determine possible flowpaths within the Leona aquifer (Fig. 4.18). A single particle was placed in the center of each cell and it was followed to the cell where it was discharged from the aquifer. Flowpaths were based on hydraulic head data and flow rates from MODFLOW model as well as user defined porosity. The porosity was defined as 20 percent, which is consistent for mixed sand and gravel sediments (Fetter, 1994, p. 86).

Groundwater flows toward the margins of the aquifer and to the southeast. Two main hydrogeologic divides are separated by converging flowpaths at Clear Fork of Plum Creek. MODPATH also calculates the travel time of particles from the point of recharge to discharge. The average traveltime was 13 years. Minimum and maximum travel times were 73 days and 70 years, respectively.

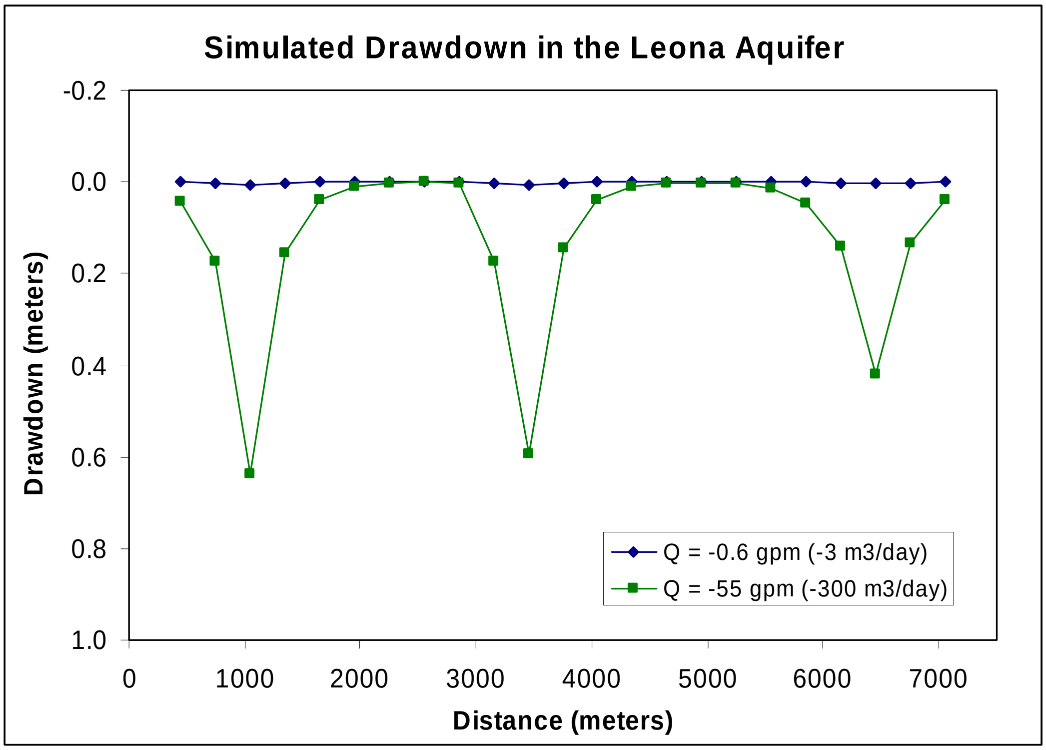


Figure 4.17. Simulated drawdown in the Leona aquifer.

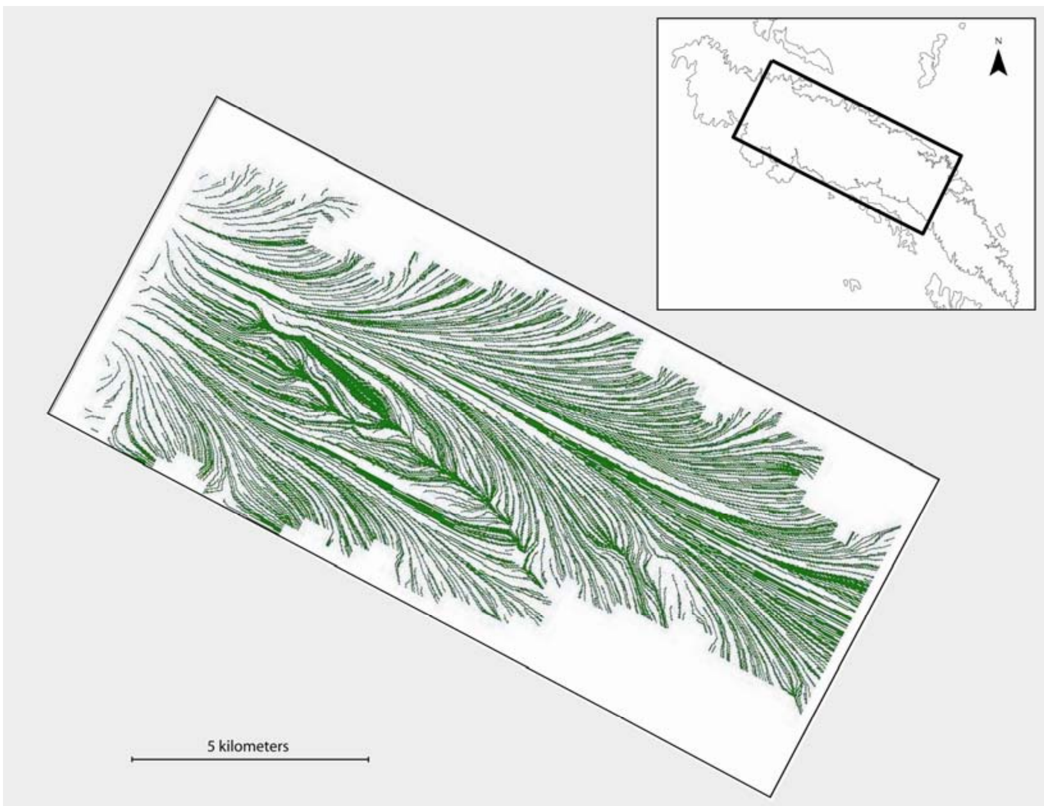


Figure 4.18. Potential flow paths in the Leona aquifer.

The result of a groundwater model is dependant on the quality and quantity of data available. Some groundwater models produce non-unique solutions because some data are poorly constrained. This model would be improved with further field tests determining specific yield, aquifer-scale distribution of lithofacies, and incorporating a heterogeneous distribution of hydraulic conductivity. The best defined data in this model are hydraulic head, with measurements collected from 47 wells. The observation function in MODFLOW was used to compare simulated values to these measurements. Simulated temporal changes in hydraulic head were compared to a well hydrograph representing measured data. Some error is introduced by assigning a single elevation value for a 300 m by 300 m cell. This is greatest at the margins of the aquifer, where the slope of the land surface is steepest. The aquifer base was approximated as an inclined plane as described in Section 3.6. However the Leona aquifer may contain filled paleochannels or swales to create an irregular aquifer thickness. Hydraulic conductivity is best defined on the outcrop or smaller scale. Outcrops in gravel pits were the source of hydraulic conductivity data. The model extends this permeability to the aquifer-scale permeability. Hydraulic conductivity data might be misestimated and heterogeneities in hydraulic conductivity are ignored. Aquifer test would help to constrain the spatial distribution of hydraulic conductivity. Specific yield is unconstrained except for general literature values. Recharge is constrained by precipitation.

Recharge must be less than precipitation because some precipitation is lost to evapotranspiration, soil storage, and runoff. Stream discharge is constrained by estimates made on June 17, 2004. The methods used to estimate stream discharge were described in Section 3.4. The stream flow in all of the creeks, except Plum Creek, is discharge from the Leona aquifer. Plum Creek is fed by several tributaries as well as by discharge from the Leona aquifer. The volume of discharge from seeps that do not flow into the major streams is still unconstrained. Well discharge was assumed very small relative to other parts of the water budget and was ignored in the model.

5: DISCUSSION AND CONCLUSIONS

The facies observed in the Leona aquifer were formed by different sedimentary processes present in a braided river depositional environment. Each one of these facies displays a different range of hydraulic conductivity. Hydraulic conductivity may vary significantly within a single facies. This heterogeneity influences groundwater flow. Soils covering the Leona aquifer effect recharge because the hydraulic conductivity of the soil is several orders of magnitude lower than that of the aquifer material. A numerical flow model of the Leona aquifer provides further insights on recharge, pumping, potential flowpaths, and travel time along these flowpaths.

5.1 Lithofacies and Depositional Environment

Deposits of the Leona Formation near Lockhart, Texas suggest a braided river depositional environment. Braided rivers consist of a network of broad, shallow channels and rapidly shifting bars, some of which are active only during floods. Braided rivers are less sinuous and carry coarser sediment than meandering rivers (Miall, 1977).

Three types of braided river barforms are recorded in the geologic record. They are longitudinal bars, transverse bars, and point or side bars. Longitudinal bars are the most common barforms in rivers carrying gravel-sized bed load. They are elongated parallel to the flow direction and in the geologic record are massive or contain crude horizontal beds. Transverse bars are oriented with their long axis perpendicular the flow direction. Transverse bars migrate downstream as bedload avalanches down the lee slope of the bedform. As a result, the dominant sedimentary structure is planar cross stratification. Point bars or side bars in braided streams are formed in low energy areas near the edges of river channels. Point bars often form as other bedforms coalesce and they contain several different types of sedimentary structures seen in the other types of barforms. Point bars may display a fining upward sequence. Point bars are less common in braided rivers than in more sinuous meandering rivers (Miall, 1977).

The Leona Formation contains facies which are similar to those described in braided stream environments. The structureless clay lenses of Facies C are interpreted as abandoned channel plugs. In the Leona Formation, this facies is often thicker than the fine grained facies described by Miall (1977) and fine lamination is absent. Both the top and bottom surfaces are irregular suggesting that they are erosional surfaces. The carbonate sand of Facies LS represents the infilling of minor channels or scour hollows during decreased flow (Miall, 1977). The crude horizontally bedded gravel of Facies HG and the massive gravel of Facies MG is interpreted as longitudinal bars. Facies HG contains crude and often discontinuous layers of openwork gravel and gravel filled with sand or clay matrix. This layering has been attributed to fluctuations in stream discharge (Smith, 1973; and Nemec and Steel, 1984). At higher rates of discharge, larger gravel is deposited and finer material is kept in suspension. As flow wanes, sand is deposited and may infiltrate into some of the previously deposited gravel. The planar cross-bedded sandy gravel of Facies PlG is interpreted as transverse bars. In some areas, cross-bed sets grade from open gravel to gravel filled with a sandy matrix. The open and matrix-filled cross-beds are likely the result of the same mechanisms discussed for facies HG. The trough cross-beds of Facies TG represent numerous amalgamated channel deposits. Most of the channel deposits are a few centimeters to decimeters deep but trough cross-bedded channels occur which are over one meter deep.

5.2 Hydraulic Properties

Grain size distribution is closely related to depositional processes. As a result, hydraulic conductivity is also correlated to depositional processes. Facies HG and Facies PlG both contain open framework gravel as well as matrix filled gravel. This creates a high degree of variability within these facies. The geometric mean of empirical hydraulic conductivity estimates (K_{GM}) for a sample of the open framework portion of Facies HG was 11.4 cm/sec (32,319 ft/day). This is the most permeable sediment documented in the Leona aquifer. The K_{GM} for the matrix filled portion of Facies HG averaged 5.73×10^{-2} cm/sec (162 ft/day) which is similar to the K_{GM} for the matrix filled portion of Facies PlG which was 5.17×10^{-2} cm/sec (147 ft/day). The open framework portion of this facies was not sampled but its hydraulic conductivity is likely similar to the open framework gravel in facies HG. Facies TG was less common than the other facies and only one sample was collected. The K_{GM} was 4.78×10^{-3} cm/sec (13.6 ft/day) which is smaller than in the other gravel facies. Facies LS can be divided into two groups based on amount of silt and clay. The K_{GM} of Facies LS samples with less than 11 percent silt and clay averaged 1.31×10^{-2} cm/sec (37.1 ft/day). The K_{GM} of samples with higher fractions of silt and clay averaged 6.43×10^{-6} cm/sec (0.018 ft/day). The amount of silt and clay may be the result of depositional processes or diagenesis of the carbonate sand. Facies QS is most similar to the cleaner sands of Facies LS. The K_{GM} is 1.20×10^{-2} cm/sec (34.02 ft/day). The quartz sand of this facies is less prone to weathering than carbonate sand of facies LS. The channel plugs of Facies C are the least permeable material documented in the Leona aquifer. The K_{GM} was 1.56×10^{-7} cm/sec (4.4×10^{-4} ft/day).

Stratigraphic profiles and facies maps drawn on outcrop photos estimated bulk hydraulic conductivity on a larger scale. The effective hydraulic conductivity of vertical profiles range from 1.3×10^{-2} cm/sec (36.9ft/day) to 1.6×10^{-2} cm/sec (45.4 ft/day) at the HGP West outcrop, 4.0×10^{-2} cm/sec (113.4 ft/day) to 5.5×10^{-2} cm/sec (155.9 ft/day) at the HGP East outcrop, and 2.1×10^{-2} cm/sec (59.5 ft/day) to 1.4×10^{-1} cm/sec (396.9ft/day) at the GGP North and GGP South outcrops. The two outcrops in the HGP gravel pit display less variation in K_{eff} than the outcrops in the GGP gravel pit. The effective hydraulic conductivity values in all four outcrops are within one order of magnitude. All of the outcrops are located on the eastern margin of the Leona aquifer.

5.3 Implications for Groundwater Flow.

Groundwater flows preferentially through the most permeable material, which in the Leona aquifer is the open-framework gravel in parts of Facies HG and Facies PlG. The low permeability clay lenses of Facies C and muddy sand lenses of Facies LS inhibit groundwater flow. The hydraulic conductivity of the clay (C) is four orders of magnitude smaller and the hydraulic conductivity of the muddy sand (LS) is three orders of magnitude smaller than the least permeable of the gravel facies.

Facies LS and Facies C are typically lenticular units. On the sedimentary structure scale, these lenses may provide significant barriers to groundwater flow but, on outcrop and aquifer scales, they may have minimal significance because of their limited lateral continuity. The same is true for layers of open-framework gravel. Layers of open-framework gravel are centimeters thick and may not be continuous for more than a few meters. Layers of open-framework gravel are separated by pebble gravel and muddy sandy gravel. The hydraulic conductivity of muddy sandy gravel samples and pebble gravel samples averaged 7.32×10^{-3} cm/sec (20.8 ft/day) and 2.17×10^{-1} cm/sec (615.2 ft/day), respectively. Gravel facies containing large amounts of sand are common and are the least permeable of the gravel facies. The hydraulic conductivity of the Leona aquifer is strongly influenced by gravel facies containing large amounts of sand because the less continuous facies with high and low permeability are separated by this material.

The hydraulic conductivity of muddy sandy gravel samples is very similar to the average hydraulic conductivity of vertical profiles discussed in Section 4.4.4 but is an order of magnitude smaller than in the model simulations discussed in Section 4.8.

5.4 Implications of soil permeability

The soil overlying the Leona aquifer is a major factor controlling the amount of recharge. The Leona aquifer is recharged by infiltration of precipitation through the soil. Ring infiltrometer and Guelph Permeameter tests indicate that the hydraulic conductivity of the soil ranges from 6.3×10^{-6} cm/sec (0.018 ft/day) to 4.6×10^{-4} cm/sec (1.3 ft/day). This is several orders of magnitude lower than the geometric mean hydraulic conductivity of the Leona aquifer. Even though the permeability of the soil is relatively low, there are several factors which enhance recharge. The soil covering the Leona aquifer slopes between 0 percent and 8 percent and runoff is low during rainfall events. The soil also contains significant amounts of clay which has a high shrink-swell capacity. Deep desiccation cracks form during dry periods and may enhance recharge, as suggested by Holzmer (1992), until the soil is moist enough for the cracks to close. Land use is the last factor which increases recharge. A significant area above the Leona aquifer is covered by cultivated fields. Cultivation of the soil increases the permeability of the soil and the furrows left from the cultivation collect rainwater giving it more time to infiltrate into the soil.

5.5 Implications of the groundwater model

The MODFLOW model of the Leona aquifer provides several insights. The model resulted in an estimate of recharge; an assessment of the aquifer's potential as a resource, potential flow paths, and travel times from recharge to discharge along these flow paths. Building the model also highlighted areas where more data are needed to characterize the aquifer.

The model suggested that 9 percent to 20 percent of annual precipitation contributes to recharge. The lower amount of recharge occurred during a simulation of year 2003 when the annual precipitation was 629 mm (24.8 in.) and the higher amount of recharge occurred during a simulation of the first six months of 2004 when the six month precipitation total was 623 mm (24.5 in.). From 1947 to 2001 the mean annual rainfall measured in Lockhart, TX was 864 mm (34.0 in.) (NCDC, 2004). Recharge to the Leona aquifer is primarily infiltration of precipitation. Recharge does not occur until the moisture content of the soil reaches field capacity. Evaporation at the surface and transpiration through plant roots draw water out of the soil. During relatively dry periods several small precipitation events may occur with no resulting recharge. Field capacity is reached and recharge occurs during large or very frequent rainfall events.

The initial hydraulic conductivity used in the model, 270 m/day (879 ft/day), is similar to the most permeable sediments in the Leona aquifer. The empirically estimated hydraulic conductivity of 18 percent of the samples was greater than 104 m/day (340 ft/day). A high value of hydraulic conductivity was used to test the hypothesis that the aquifer scale hydraulic conductivity is dominated by the most permeable sediments. Simulations with this hydraulic conductivity did not produce realistic results because nearly all of precipitation was needed to match observed water level changes during recharge events. This is not reasonable because a portion of precipitation is lost to evapotranspiration, soil storage, and runoff. The aquifer scale permeability may be lower than initially assumed if the most permeable sediments are not laterally continuous on larger scales. The hydraulic conductivity in the model was lowered to 50 m/day (170 ft/day). The empirically estimated hydraulic conductivity of 47 percent of samples was within one order of magnitude of this value. It is also similar to the effective hydraulic conductivity (K_{eff}) calculated for stratigraphic profiles in Section 4.4.4. K_{eff} ranged from 112 m/day (369 ft/day) to 12 m/day (28 ft/day). This value of hydraulic conductivity, 50 m/day (170 ft/day), produced the best solution. This value of hydraulic conductivity is comparable to gravelly sand, gravelly muddy sand, and sand sediment textures. It is also similar to the matrix filled portions of Facies HG and Facies PlG.

Simulated pumping wells provide insights on the potential of the Leona aquifer as a water resource. Pumping test simulations were run for a period of 61 days with no recharge and 0.6 mm/day (0.024 in/day) of evapotranspiration. At a pumping rate of 0.04 l/sec (0.6 gpm), 3 mm (0.12 in.) to 6 mm (0.24 in) of drawdown occurred. At a pumping rate of 3.5 l/sec (55 gpm) 0.3 m (1 ft) to 0.6 m (2 ft) of drawdown occurred. In addition to the drawdown due to pumping, the water table fell 0.3 m (1 ft) to 0.5 m (1.6 ft) as a result of natural drainage of the aquifer. At the higher pumping rate the cone of depression extended 900 m (2,953 ft) to 1,200 m (3,937 ft) away from the well. These results suggest that the Leona aquifer can support pumping rates which are typical of domestic wells but higher rates of use may result in dewatering of the aquifer, given its small saturated thickness. A large number of domestic wells in a small area could cause significant amounts of drawdown.

Potential flow paths generated by MODPATH illustrate the direction of groundwater flow in the Leona aquifer. Groundwater flows away from hydrogeologic divides (Fig. 4.6 and Fig 4.18) toward the margins of the aquifer and toward Clear Fork Plum Creek which lies between the divides. Groundwater also flows toward the southeast end of the aquifer. Numerous springs and seeps at the perched edge of the aquifer support this flow path model. Ground water also discharges into Clear Fork of Plum Creek and smaller creeks. When the water table is low, water does not discharge into the upper reaches of Clear Fork Plum Creek. Groundwater which does not discharge at the margin of the aquifer or into streams eventually infiltrates into the permeable Wilcox group bedrock to the southeast. Travel times calculated by MODPATH show that the average time needed for a particle to travel from recharge to discharge is 13 years. Minimum and maximum travel times were 73 days and 70 years, respectively. These travel times imply that conservative contaminants which enter the aquifer could remain in the aquifer for several decades. Oil-brine contamination in the Larremore oil field (Fig. 1.5) from the 1940's could potentially remain in the aquifer. The travel times estimated for the Leona aquifer are very short in a geologic context.

Appendix A: Results of Grain-Size Analyses

The grain-size distribution of sediment samples was determined in order to obtain empirical estimates of permeability. Sieve and hydrometer analyses were performed on all samples except well cemented samples. The grain-size analyses were completed using the methodology described by American Society for Testing and Material (ASTM) standard D 422-63 (ASTM, 2003b). ASTME-11 sieve numbers 3”, 2”, 1.5”, 1”, ¾”, 3/8”, 4, 10, 16, 30, 50, 100, 200, and 270 were used for the sieve analyses and an ASTM 151H hydrometer was used for the analysis of sediment finer than the No. 270 sieve. Additional details describing the procedure of grain-size analyses can be found in ASTM standard D 422-63 (ASTM, 2003b). This appendix lists the results of the grain-size analyses.

		HGP1 Facies QS		HGP3 Facies HG		HGP5 Facies MG		HGP6 Facies PIG		HGP7 Facies LS	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000		50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	100.0	38.1000	85.1	38.1000	100.0	38.1000	100.0	38.1000	100.0
	1"	25.4000	100.0	25.4000		25.4000	92.5	25.4000	96.0	25.4000	100.0
	3/4"	19.0500	100.0	19.0500	50.0	19.0500	85.1	19.0500	94.2	19.0500	100.0
	3/8"	9.5250	100.0	9.5250	20.3	9.5250	62.5	9.5250	83.9	9.5250	100.0
ASTME-11	No.4	4.7600	100.0	4.7600		4.7600	41.3	4.7600	62.4	4.7600	100.0
Sieves	No. 10	2.0000	99.6	2.0000	6.4	2.0000	25.1	2.0000	32.1	2.0000	100.0
	No. 16	1.1800	99.2	1.1800	6.1	1.1800	19.9	1.1800	21.1	1.1800	100.0
	No. 30	0.6000	98.8	0.6000	5.9	0.6000	16.5	0.6000	17.2	0.6000	100.0
	No. 50	0.3000	84.9	0.3000	5.6	0.3000	14.3	0.3000	12.5	0.3000	98.7
	No. 100	0.1500	10.3	0.1500	4.9	0.1500	11.2	0.1500	7.6	0.1500	42.0
	No. 200	0.0750	2.4	0.0750	4.5	0.0750	7.8	0.0750	6.3	0.0750	10.5
	No. 270	0.0530	1.9	0.0530	4.3	0.0530	6.9	0.0530	6.2	0.0530	9.5
				0.0144	3.9	0.0250	6.0	0.0317	6.3	0.0365	9.4
				0.0091	3.4	0.0166	5.6	0.0202	6.1	0.0232	8.5
				0.0059	2.6	0.0115	5.2	0.0117	5.8	0.0134	8.3
				0.0042	2.0	0.0068	4.4	0.0069	5.1	0.0095	7.8
Hydrometer				0.0029	1.5	0.0045	3.5	0.0046	3.9	0.0067	7.5
				0.0016	1.3	0.0030	2.5	0.0030	3.0	0.0033	5.5
				0.0013	1.2	0.0017	1.8	0.0017	2.6	0.0014	3.3
				0.0011	1.1	0.0014	1.6	0.0013	2.5		
						0.0011	1.3	0.0012	2.3		

		HGP8 Facies PIG		HGP9 Facies HG or MG		GGP1 Facies C		GGP2 Facies PIG		GGP 3 Facies LS	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0
	1"	25.4000	100.0	25.4000		25.4000	100.0	25.4000	98.2	25.4000	100.0
	3/4"	19.0500	98.2	19.0500	85.6	19.0500	100.0	19.0500	95.7	19.0500	100.0
	3/8"	9.5250	89.0	9.5250	47.9	9.5250	100.0	9.5250	71.7	9.5250	100.0
ASTME-11	No.4	4.7600	58.6	4.7600	29.0	4.7600	100.0	4.7600	41.3	4.7600	100.0
Sieves	No. 10	2.0000	34.8	2.0000	21.2	2.0000	100.0	2.0000	25.0	2.0000	100.0
	No. 16	1.1800	31.4	1.1800	20.2	1.1800	100.0	1.1800	22.1	1.1800	100.0
	No. 30	0.6000	26.9	0.6000	19.1	0.6000	100.0	0.6000	18.9	0.6000	100.0
	No. 50	0.3000	15.6	0.3000	15.6	0.3000	100.0	0.3000	12.6	0.3000	99.9
	No. 100	0.1500	6.6	0.1500	8.3	0.1500	100.0	0.1500	5.3	0.1500	79.0
	No. 200	0.0750	5.1	0.0750	6.3	0.0750	100.0	0.0750	4.1	0.0750	31.9
	No. 270	0.0530		0.0530	5.9	0.0530	100.0	0.0530	4.0	0.0530	27.1
		0.0326	5.4	0.0304	5.5	0.0251	100.0	0.0268	4.5	0.0347	18.9
		0.0209	4.5	0.0194	5.3	0.0164	93.8	0.0209	4.1	0.0223	16.7
		0.0121	4.4	0.0114	4.7	0.0097	89.1	0.0121	4.1	0.0119	15.5
		0.0085	4.0	0.0068	3.6	0.0071	82.8	0.0086	3.9	0.0092	14.2
Hydrometer		0.0060	3.5	0.0046	2.7	0.0052	73.8	0.0061	3.7	0.0066	13.3
		0.0031	2.5	0.0030	2.1	0.0028	54.7	0.0031	3.0	0.0034	10.7
		0.0019	1.9	0.0017	1.5	0.0018	42.5	0.0018	2.6	0.0014	6.3
		0.0013	1.9	0.0013	1.5	0.0013	33.7	0.0013	2.1		
				0.0012	1.2	0.0012	30.0				

		GGP4 Facies HG		GGP5 Facies PIG		GGP6 Facies PIG		GGP7 Facies TG		GGP8 Gfacies HG	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0
	1"	25.4000	98.2	25.4000	100.0	25.4000	100.0	25.4000	100.0	25.4000	100.0
	3/4"	19.0500	96.0	19.0500	100.0	19.0500	98.1	19.0500	98.7	19.0500	97.9
	3/8"	9.5250	62.8	9.5250	95.7	9.5250	83.2	9.5250	86.6	9.5250	74.0
ASTME-11	No.4	4.7600	30.3	4.7600	87.5	4.7600	41.7	4.7600	51.4	4.7600	42.2
Sieves	No. 10	2.0000	15.2	2.0000	69.6	2.0000	13.6	2.0000	17.9	2.0000	19.6
	No. 16	1.1800	13.0	1.1800	60.3	1.1800	9.7	1.1800	13.3	1.1800	9.2
	No. 30	0.6000	11.7	0.6000	47.0	0.6000	8.4	0.6000	11.7	0.6000	7.0
	No. 50	0.3000	10.2	0.3000	14.5	0.3000	8.0	0.3000	11.2	0.3000	6.2
	No. 100	0.1500	6.8	0.1500	4.4	0.1500	5.6	0.1500	10.3	0.1500	4.6
	No. 200	0.0750	5.2	0.0750	3.9	0.0750	4.4	0.0750	9.6	0.0750	4.1
	No. 270	0.0530	5.0	0.0530	3.8	0.0530	4.3	0.0530	9.3	0.0530	4.0
		0.0241	5.0	0.0372	3.7	0.0243	4.3	0.0252	9.0	0.0293	
		0.0188	4.8	0.0236	3.3	0.0190	4.2	0.0164	8.6	0.0188	3.9
		0.0110	4.7	0.0136	3.2	0.0110	4.1	0.0098	8.0	0.0110	3.7
		0.0078	4.5	0.0095	3.1	0.0079	3.9	0.0071	7.6	0.0079	3.5
Hydrometer		0.0056	4.2	0.0068	2.7	0.0056	3.8	0.0051	7.0	0.0057	3.1
		0.0028	3.5	0.0034	2.5	0.0028	3.3	0.0027	5.6	0.0030	2.5
		0.0017	3.2	0.0014	1.8	0.0017	3.1	0.0017	5.1	0.0018	2.1
		0.0012	2.7			0.0012	2.7	0.0012	4.4	0.0013	1.6
								0.0011	4.3	0.0012	1.4

		GGP 9 Soil		GGP10 Facies QS		GGP 11 Soil		GGP FLT1 Facies MG		GGP FLT2 Facies LS	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
ASTME-11 Sieves	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0
	1"	25.4000	100.0	25.4000	100.0	25.4000	100.0	25.4000	100.0	25.4000	100.0
	3/4"	19.0500	100.0	19.0500	100.0	19.0500	100.0	19.0500	94.2	19.0500	100.0
	3/8"	9.5250	100.0	9.5250	100.0	9.5250	97.3	9.5250	69.2	9.5250	98.5
	No.4	4.7600	100.0	4.7600	100.0	4.7600	95.9	4.7600	41.6	4.7600	94.7
	No. 10	2.0000	100.0	2.0000	100.0	2.0000	95.4	2.0000	19.4	2.0000	89.8
	No. 16	1.1800	99.7	1.1800	100.0	1.1800	95.3	1.1800	13.9	1.1800	88.7
	No. 30	0.6000	99.3	0.6000	99.7	0.6000	94.9	0.6000	10.2	0.6000	86.9
	No. 50	0.3000	95.4	0.3000	24.6	0.3000	93.3	0.3000	8.5	0.3000	70.6
	No. 100	0.1500	79.6	0.1500	1.3	0.1500	87.4	0.1500	6.8	0.1500	9.3
	No. 200	0.0750	63.8	0.0750	0.5	0.0750	75.7	0.0750	6.0	0.0750	7.5
	No. 270	0.0530	58.0	0.0530	0.5	0.0530	72.7	0.0530	5.6	0.0530	7.3
Hydrometer		0.0251	52.0			0.0251	68.3	0.0251	5.4	0.0251	6.9
		0.0164	51.3			0.0164	63.8	0.0164	5.3	0.0164	6.9
		0.0097	43.5			0.0097	59.2	0.0097	4.7	0.0097	6.9
		0.0071	40.9			0.0071	55.0	0.0071	4.5	0.0071	6.9
		0.0052	39.0			0.0052	48.6	0.0052	3.6	0.0052	6.8
		0.0028	36.7			0.0028	34.9	0.0028	2.4	0.0028	5.3
		0.0018	35.1			0.0018	31.9	0.0018	1.9	0.0018	4.3
		0.0013	32.5			0.0013	30.7	0.0013	1.8	0.0013	4.2
		0.0012	30.9			0.0012	30.4	0.0012	1.6	0.0012	3.2

		GGP FLT4 Facies HG		GGP FLT5 Facies HG		GGP FLT6 Facies HG		DAV 015		DAV041	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	96.4	38.1000	100.0	38.1000	100.0	38.1000	95.6	38.1000	100.0
	1"	25.4000	93.6	25.4000	100.0	25.4000	88.3	25.4000	92.6	25.4000	100.0
	3/4"	19.0500	92.5	19.0500	96.6	19.0500	83.0	19.0500	90.2	19.0500	96.8
	3/8"	9.5250	72.9	9.5250	77.2	9.5250	49.6	9.5250	70.6	9.5250	64.4
ASTME-11	No.4	4.7600	49.3	4.7600	39.2	4.7600	29.0	4.7600	46.7	4.7600	27.6
Sieves	No. 10	2.0000	30.1	2.0000	16.0	2.0000	20.3	2.0000	33.3	2.0000	9.4
	No. 16	1.1800	24.6	1.1800	12.7	1.1800	18.7	1.1800	29.4	1.1800	7.8
	No. 30	0.6000	20.3	0.6000	10.8	0.6000	16.5	0.6000	23.0	0.6000	6.9
	No. 50	0.3000	16.5	0.3000	9.3	0.3000	9.0	0.3000	11.9	0.3000	6.0
	No. 100	0.1500	5.5	0.1500	5.5	0.1500	3.8	0.1500	5.2	0.1500	4.9
	No. 200	0.0750	4.0	0.0750	3.7	0.0750	3.2	0.0750	4.0	0.0750	3.9
	No. 270	0.0530	3.8	0.0530	3.5	0.0530	3.1	0.0530	3.9	0.0530	3.5
		0.0251	4.2	0.0251	3.5	0.0355	3.1	0.0363	3.9	0.0251	3.6
		0.0164	4.0	0.0164	3.2	0.0225	3.0	0.0230	3.6	0.0164	3.4
		0.0097	3.7	0.0097	3.0	0.0119	2.9	0.0133	3.6	0.0097	3.0
		0.0071	3.6	0.0071	2.9	0.0092	2.8	0.0095	3.3	0.0071	2.8
Hydrometer		0.0052	3.6	0.0052	2.5	0.0066	2.6	0.0067	3.1	0.0052	2.6
		0.0028	2.3	0.0028	1.7	0.0033	1.9	0.0033	2.2	0.0028	1.6
		0.0018	1.8	0.0018	1.4	0.0014	1.6	0.0014	1.6	0.0018	1.3
		0.0013	1.6	0.0013	1.3					0.0013	1.1
		0.0012	1.4	0.0012	1.2					0.0012	1.0

		LL2 Facies MG		LL3 Facies C		LL4 Facies LS		LL6 Facies C		LL7 Facies LS	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer	mm	% finer
ASTME-11 Sieves	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0	38.1000	100.0
	1"	25.4000		25.4000	100.0	25.4000	100.0	25.4000	100.0	25.4000	100.0
	3/4"	19.0500	85.6	19.0500	100.0	19.0500	100.0	19.0500	100.0	19.0500	100.0
	3/8"	9.5250	47.9	9.5250	100.0	9.5250	100.0	9.5250	98.9	9.5250	91.1
	No.4	4.7600	29.0	4.7600	100.0	4.7600	96.6	4.7600	97.7	4.7600	86.6
	No. 10	2.0000	21.2	2.0000	100.0	2.0000	94.6	2.0000	97.0	2.0000	82.5
	No. 16	1.1800	16.5	1.1800	99.9	1.1800	93.5	1.1800		1.1800	81.2
	No. 30	0.6000	13.4	0.6000	99.7	0.6000	89.2	0.6000	97.0	0.6000	79.3
	No. 50	0.3000	8.5	0.3000	97.9	0.3000	66.2	0.3000		0.3000	58.1
	No. 100	0.1500	3.9	0.1500	85.5	0.1500	25.5	0.1500		0.1500	22.8
	No. 200	0.0750	3.3	0.0750	68.0	0.0750	18.5	0.0750	95.6	0.0750	17.5
	No. 270	0.0530	3.1	0.0323	59.2	0.0530	17.9	0.0530		0.0530	16.7
Hydrometer		0.0326	3.1	0.0207	54.5	0.0356	17.7	0.0273	82.6	0.0316	
		0.0208	2.8	0.0122	49.8	0.0225	17.5	0.0175	78.6	0.0203	15.6
		0.0121	2.7	0.0088	43.6	0.0131	15.8	0.0103	73.9	0.0118	14.5
		0.0070	2.5	0.0064	34.2	0.0093	13.9	0.0074	69.6	0.0069	12.9
		0.0046	2.2	0.0034	18.7	0.0067	12.0	0.0054	63.2	0.0046	10.4
		0.0030	1.9	0.0014	12.1	0.0033	9.5	0.0029	41.6	0.0030	8.7
		0.0017	1.7			0.0014	6.3	0.0018	32.3	0.0017	6.2
		0.0014	1.6					0.0013	24.0	0.0013	6.1
		0.0012	1.4					0.0012	20.9		

		LL8 Facies MG		LR 1 Facies QS		LR4 Weathered		LR5 Weathered	
		mm	% finer	mm	% finer	mm	% finer	mm	% finer
	3"	76.2000	100.0	76.2000	100.0	76.2000	100.0	76.2000	100.0
	2"	50.8000		50.8000	100.0	50.8000	100.0	50.8000	100.0
	1.5"	38.1000	90.9	38.1000	100.0	38.1000	89.8	38.1000	100.0
	1"	25.4000		25.4000	100.0	25.4000	89.8	25.4000	100.0
	3/4"	19.0500	83.5	19.0500	100.0	19.0500	82.1	19.0500	100.0
	3/8"	9.5250	52.3	9.5250	100.0	9.5250	70.8	9.5250	99.6
ASTME-11	No.4	4.7600	26.4	4.7600	100.0	4.7600	57.8	4.7600	97.7
Sieves	No. 10	2.0000	16.6	2.0000	100.0	2.0000	46.0	2.0000	93.9
	No. 16	1.1800	15.7	1.1800	100.0	1.1800	42.0	1.1800	90.8
	No. 30	0.6000	14.4	0.6000	100.0	0.6000	37.1	0.6000	84.0
	No. 50	0.3000	11.2	0.3000	99.9	0.3000	32.2	0.3000	72.0
	No. 100	0.1500	7.6	0.1500	89.8	0.1500	26.8	0.1500	48.4
	No. 200	0.0750	5.6	0.0750	20.5	0.0750	21.6	0.0750	33.3
	No. 270	0.0530	5.3	0.0530	16.3	0.0306	17.7	0.0530	31.0
Hydrometer		0.0293	5.1	0.0364	11.0	0.0198	16.4	0.0325	26.5
		0.0189	4.7	0.0232	9.7	0.0118	14.6	0.0211	23.4
		0.0111	4.2	0.0135	8.2	0.0084	13.1	0.0124	21.4
		0.0066	3.6	0.0094	7.8	0.0061	11.6	0.0087	19.3
		0.0045	2.9	0.0068	7.1	0.0031	9.3	0.0063	17.7
		0.0030	2.2	0.0034	4.9	0.0013	7.2	0.0032	14.3
		0.0017	2.0	0.0014	3.1			0.0014	11.2
		0.0013	1.8						
		0.0011	1.7						

Appendix B: Permeameter Sample Descriptions

Samples were collected to measure permeability in the laboratory with a constant head or falling head permeameter. When collecting samples to take into the laboratory, it is important to preserve the *in situ* conditions. These conditions include packing and orientation of clasts and the degree of cementation. Where possible, samples were collected as undisturbed blocks of sediment (US). These blocks of sediment were trimmed by hand to fit in the laboratory permeameter. Disturbed samples (DS) were collected where the sediment was unconsolidated or poorly cemented. These samples were repacked into the permeameter. Following are descriptions of these samples.

Sample Number	Sample Type	Description	Average area (cm2)	Length (cm)	Dry mass (g)	Permeameter type	Measured K (cm/sec)
GGP FLT1	DS-2	Limestone pebble gravel, massive, well rounded gravel clasts, some flat grains.	181 (repacked)	11.5 (repacked)	3900	constant head	2.3E+00
GGP FLT2	US-2	Gravelly carbonate sand, weak planar cross bedding, gravel clasts well rounded, moderately cemented, some gravel clasts contain sparry calcite on surface.	133	20	4462	constant head	2.6E-02
GGP FLT3	US-9	Limestone gravel, well rounded clasts, well to moderately cemented with calcite cement, clast supported.	92	18	n/a	constant head	9.7E-02
GGP FLT4	US-3	Limestone muddy sandy gravel, horizontal bedding, gravel clasts well rounded, poorly to moderately cemented, clast supported.	106	18	4274	constant head	3.8E-03
GGP FLT5	US-1	Limestone pebble gravel, gravel clasts well rounded, poorly to moderately cemented, crude horizontal stratification, some layers contain no sand, clast supported.	103	18	4212	constant head	2.8E-02
GGP FLT6	US-4	Limestone and chert pebble gravel, gravel clasts well rounded, horizontal bedded, poorly to moderately cemented, matrix supported.	71	11	2060	constant head	3.3E-03
HGP 1	US-7	Quartz sand, planar cross bedded, poorly cemented with calcite cement	15	5.5	143.2	falling head	8.4E-04
HGP2	US-10	Carbonate sand, structureless, well to moderately cemented.	17	6.5	n/a	falling head	2.6E-04
HGP 7	US-6	Muddy carbonate sand, poor to moderately cemented.	48	3.6	n/a	constant head	2.0E-03

Sample Number	Sample Type	Description	Average area (cm2)	Length (cm)	Dry mass (g)	Permeameter type	Measured K (cm/sec)
DAV 015	DS-3	Muddy sandy gravel, well rounded gravel clasts, poorly cemented.	87 (repacked)	12.5 (repacked)	1922	constant head	1.2E-01
DAV 041	DS-1	Limestone pebble gravel, well rounded to rounded, some flattened clasts, some grains cemented with calcite cement.	181 (repacked)	10 (repacked)	3263	constant head	5.8E+00
LL 7	US-8	Gravelly muddy carbonate sand, massive, poorly cemented.	17.5	8	247	falling head	4.0E-04
LR 1	US-5	Muddy quartz sand, planar cross bedded, poorly cemented.	20	8.5	319	constant head	2.2E-03

Appendix C: Water-Well Survey Results

Numerous wells have been completed in the Leona aquifer in Caldwell County. Many of the wells are hand dug wells; some are more than 100 years old. Other wells are modern drilled wells. A survey was conducted to determine how many wells are in the area and how groundwater is used. Wells were located using the TWDB groundwater database, visual inspection from roadways, or by information from landowners. This survey is not a complete inventory of all the wells in the area due to the large number of wells. The following information was collected when possible for each well included in the survey; well diameter, well depth, casing materials, depth to water from land surface, and well use. Figure A-1 shows the location of these wells. Following are the results of this survey.

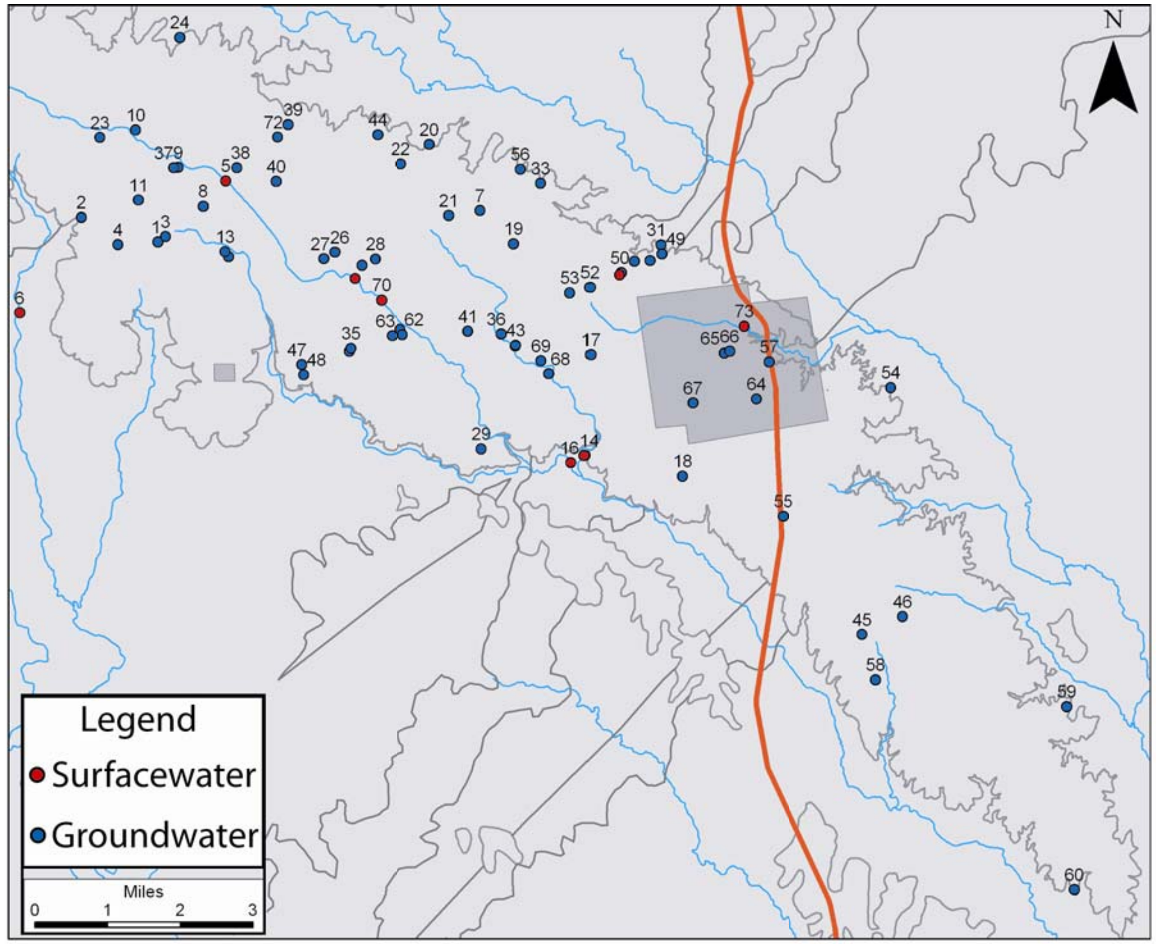


Figure A-1. Location of surveyed water wells, groundwater chemistry, and surface water chemistry measurements.

Well Number	Well Diameter (ft)	Total Depth (ft bls)	Well Use	Casing Information	Comments
1	n/a	n/a	abandoned	n/a	windmill
2	3.0	20.0	unused	n/a	
3	4.0	24.6	irrigation	4' metal culvert pipe, top 8.5'	snakes in well
4	3.0	28.9	abandoned	3' cement culvert pipe	uncovered, windmill
7	0.4	n/a	domestic	n/a	
8	3.3	22.6	unused	brick, top 3'	
9	2.7	22.8	unused	n/a	poor water quality reported
10	2.3	15.9	domestic	brick	
11	2.0	n/a	abandoned	n/a	
12	3.0	22.1	abandoned	brick, top 9'	
13	6.5	14.6	livestock	cement ring at surface	
14	2.5	n/a	domestic	brick at surface	near Boggy Creek
17	3.5	n/a	domestic	brick	used heavily in the summer
18	2.5	n/a	domestic	brick	poor water quality reported
19	4.0	n/a	domestic	n/a	
20	2.5	n/a	abandoned	cement culvert pipe, tin roofing	uncovered
21	2.5	29.3	unused	metal culvert pipe	historical observation well
22	3.2	n/a	unused	cement at surface	
23	4.0	25.2	domestic	brick, top 1.5', conglomerate blocks 3'	
24	4.0	n/a	domestic	n/a	
25	2.8	19.7	livestock	brick at top	
26	3.1	10.6	livestock	brick, top 2.75'	
27	3.2	16.6	livestock	brick, top 6.5'	snake in well
28	3.0	26.2	livestock	brick, top 4.5'	
29	2.5	22.0	unused	cement rings	
30	2.7	22.3	abandoned	brick	uncovered, windmill, snake in well
32	2.5	38.1	abandoned	brick	uncovered
33	4.0	n/a	unused	cement ring at surface	
34	0.5	n/a	domestic	pvc pipe	original well was 2.7' in diameter
35	0.7	26.0	unused	pvc pipe, top 6'	
36	3.0	13.3	abandoned	brick	near Boggy Creek
37	n/a	n/a	domestic	n/a	
38	n/a	n/a	unknown	n/a	
39	n/a	n/a	domestic	n/a	
40	n/a	n/a	unknown	n/a	

Well Number	Well Diameter (ft)	Total Depth (ft bls)	Well Use	Casing Information	Comments
41	5.8	n/a	abandoned	brick, top 13'	
42	4.6	20.5	unused	n/a	snakes in well.
43	2.3	20.2	unused	n/a	well diameter widens to approx. 4'
44	2.7	n/a	abandoned	n/a	
45	n/a	n/a	unknown	n/a	
46	n/a	n/a	unknown	n/a	
47	5.0	n/a	unused	n/a	well in cellar.
48	4.0	19.4	abandoned	limestone blocks	uncovered, windmill, reportedly does not go dry when nearby wells go dry
49	4.7	20.4	abandoned	stone blocks, top 3.5	uncovered
50	3.3	32.3	abandoned	n/a	
52	3.2	16.9	irrigation	brick	uncovered, reportedly a good well
53	2.9	22.5	abandoned	brick	uncovered
54	0.5	n/a	domestic	n/a	draws water from the Wilcox aquifer
55	4.0	n/a	domestic	n/a	windmill
56	3.0	15.4	unused	cement, top 3.3', limestone blocks	
57	2.7	17.0	unused	brick, top 3'	
58	0.4	138.3	livestock	n/a	draws water from the Wilcox aquifer
59	0.4	n/a	domestic/livestock	n/a	
60	0.3	n/a	abandoned	n/a	abandoned because of low yield
61	4.7	25.8	unused	cement, top 5'	
62	6.0	26.1	unused	cement, top 2.5', brick, 2.5'	
63	4.0	n/a	domestic	n/a	reportedly did not go dry duing 1950's drought when nearby wells went dry
64	0.4	n/a	domestic	n/a	
65	0.4	n/a	domestic	n/a	
66	1.33	22.7	domestic	n/a	
67	0.40	n/a	domestic	n/a	
68	0.40	n/a	unused	n/a	
69	0.50	n/a	domestic	n/a	
72	3.00	n/a	irrigation	brick and rock, top 6'	

domestic = well used for household use or lawn and garden irrigation

livestock = well used to water livestock

irrigation = well used for irrigation during dry seasons

unused = well that is not used but maintained

abandoned = well that is not used and not maintained

n/a = data not available

Appendix D: Water Level Monitoring Results

The water level in the Leona aquifer was monitored to observe the seasonal changes in the water table elevation and the response to precipitation. Water level measurements were collected in April, May, and June of 2003 and again in November of 2003. The water level in well #36 was measured weekly from May 31, 2003, to July 3, 2004, in order to observe changes at shorter time intervals. Water level measurements were collected using a steel tape measure or an e-line. Sixty three wells were included in the first round of measurements and 40 wells in the second survey. Thirty nine wells were included in both surveys. Following are the water level monitoring results.

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
2	633	05/31/03	10.83	622.17	
		06/14/03	10.13	622.88	
3	625	05/31/03	12.43	612.57	
		06/14/03	11.08	613.92	
		11/08/03	13.54	611.46	
4	639	06/16/03	11.05	627.95	
		11/08/03	14.50	624.50	
7	595	06/17/03	12.21	582.79	
8	622	06/17/03	11.79	610.21	
		11/11/03	12.87	609.13	
9	623	06/17/03	7.33	615.67	
10	629	06/18/03	3.00	626.00	
		11/08/03	5.96	623.04	
11	635	06/18/03	11.83	623.17	
		11/08/03	14.25	620.75	
12	614	06/18/03	11.08	602.92	
		11/08/03	12.54	601.46	
13	614	06/18/03	11.25	602.75	
		11/08/03	12.75	601.25	
14	507	06/19/03	9.25	497.75	
		11/06/03	8.80	498.20	
17	555	06/19/03	11.75	543.25	
		11/11/03	16.92	538.08	
18	533	06/19/03	19.67	513.33	
		11/15/03	21.50	511.50	
19	586	06/20/03	23.08	562.92	
		11/15/03	24.96	561.04	
20	591	06/20/03	9.70	581.30	
21	591	06/20/03	20.58	570.42	
		11/06/03	22.83	568.17	
22	602	06/20/03	23.92	578.08	
		11/11/03	26.25	575.75	

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
23	636	06/21/03	8.72	627.28	
24	635	06/21/03	11.35	623.65	
		11/08/03	12.33	622.67	
25	590	06/23/03	9.75	580.25	
		06/27/03	9.96	580.04	
		07/23/03	10.34	579.66	
		11/08/03	10.21	579.79	
26	589	06/23/03	4.75	584.25	
		11/08/03	5.25	583.75	
27	588	06/23/03	4.38	583.62	
		06/27/03	4.59	583.41	
		11/08/03	5.09	582.91	
28	594	06/23/03	14.13	579.87	
		06/27/03	14.21	579.79	
		11/08/03	14.80	579.20	
29	555	06/23/03	14.31	540.69	
		11/15/03	16.92	538.08	
30	571	06/25/03	20.25	550.75	
		11/06/03	22.50	548.50	
31	540	06/25/03	23.25	516.75	
33	580	06/25/03	5.83	574.17	
		11/11/03	7.25	572.75	
34	600	06/25/03	16.03	583.97	
		11/15/03	21.45	578.55	
35	599	06/25/03	19.88	579.12	
		11/15/03	24.17	574.83	

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
36	562	05/31/03	5.38	556.62	
		06/14/03	5.05	556.95	
		06/16/03	5.13	556.87	
		06/18/03	5.22	556.78	
		06/19/03	5.28	556.72	
		06/20/03	5.30	556.70	
		06/21/03	5.35	556.65	
		06/23/03	5.38	556.62	
		06/25/03	5.44	556.56	
		06/26/03	5.47	556.53	
		06/27/03	5.47	556.53	
		06/28/03	5.51	556.49	
		06/30/03	5.55	556.45	
		07/01/03	5.57	556.43	
		07/02/03	5.63	556.37	
		07/17/03	5.84	556.16	
		07/21/03	5.88	556.12	
		07/23/03	5.97	556.03	
		07/25/03	6.00	556.00	
		07/26/03	6.03	555.97	
		07/28/03	6.05	555.95	
		07/29/03	6.06	555.94	
		07/30/03	6.09	555.91	
		07/31/03	6.10	555.90	
		08/01/03	6.12	555.88	
		08/04/03	6.19	555.81	
		08/11/03	6.31	555.69	
		08/19/03	6.49	555.51	
		08/26/03	6.62	555.38	
		08/31/03	6.73	555.27	
		09/07/03	6.86	555.14	
		09/13/03	6.61	555.39	
		09/20/03	6.63	555.37	
		09/27/03	6.74	555.26	
		10/04/03	6.87	555.13	
		10/11/03	6.98	555.02	
		10/17/03	7.05	554.95	
		10/25/03	7.16	554.84	
		11/02/03	7.30	554.70	
		11/06/03	7.38	554.62	
		11/11/03	7.45	554.55	
		11/15/03	7.51	554.49	
		11/22/03	7.62	554.38	
		11/29/03	7.75	554.25	
		12/06/03	7.86	554.14	
		12/13/03	7.98	554.02	
		12/20/03	8.10	553.90	
		01/04/04	8.35	553.65	
		01/10/04	8.44	553.56	
		01/17/04	7.99	554.01	

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
36 (cont.)	562	01/24/04	8.34	553.66	
		01/31/04	8.44	553.56	
		02/07/04	8.53	553.47	
		02/14/04	7.94	554.06	
		02/21/04	7.94	554.06	
		02/29/04	7.94	554.06	
		03/06/04	7.98	554.02	
		03/13/04	8.05	553.95	
		03/27/04	8.20	553.80	
		04/03/04	8.30	553.70	
		04/10/04	8.36	553.64	
		04/17/04	8.41	553.59	
		04/24/04	8.47	553.53	
		05/01/04	8.52	553.48	
		05/08/04	8.58	553.42	
		05/15/04	7.97	554.03	
		05/29/04	8.09	553.91	
		06/05/04	8.03	553.97	
		06/10/04	6.68	555.32	
		06/12/04	7.06	554.94	
		06/19/04	7.20	554.80	
		06/26/04	7.25	554.75	
		07/03/04	6.21	555.79	
37	623	05/31/03	12.47	610.53	
38	621	05/31/03	15.42	605.58	
39	636	05/31/03	13.16	622.84	
40	617	05/31/03	21.33	595.67	
41	573	05/31/03	11.99	561.01	
		11/06/03	14.83	558.17	
42	558	05/31/03	8.82	549.18	
		11/15/03	10.92	547.08	
43	558	05/31/03	11.93	546.07	
		11/15/03	12.38	545.62	
44	610	05/31/03	10.20	599.80	
45	490	05/31/03	31.08	458.92	
46	485	05/31/03	27.00	458.00	
47	610	06/26/03	11.58	598.42	
		11/15/03	15.25	594.75	

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
48	601	06/26/03	9.30	591.70	
		11/15/03	11.42	589.58	
49	564	06/28/03	14.25	549.75	
		11/06/03	17.42	546.58	
50	571	06/28/03	14.25	556.75	
		11/06/03	14.71	556.29	
52	558	06/28/03	7.03	550.97	
		08/11/03	8.10	549.90	
		11/06/03	8.74	549.26	
53	565	06/28/03	8.90	556.10	
		08/11/03	9.30	555.70	
		11/06/03	10.58	554.42	
54	498	06/28/03	29.62	468.38	
55	526	06/28/03	30.50	495.50	
		11/11/03	32.33	493.67	
56	581	06/28/03	3.08	577.92	
57	518	06/30/03	8.92	509.08	
		11/06/03	9.25	508.75	
58	486	06/30/03	42.22	443.78	
		11/15/03	41.72	444.28	
59	465	06/30/03	69.17	395.83	
60	431	07/01/03	52.35	378.65	
61	578	07/01/03	13.50	564.50	
62	581	07/01/03	14.00	567.00	
63	584	07/01/03	18.00	566.00	
64	534	07/02/03	20.46	513.54	
		11/11/03	21.00	513.00	

Well Number	Elevation of Land Surface (ft asl)	DATE	Depth to Water Table (ft bls)	Water Table Elevation (ft asl)	Comments
65	540	07/02/03	22.17	517.83	pumping in progress during water level measurement
		11/11/03	23.17	516.83	
66	535	07/02/03	18.92	516.08	
67	545	07/02/03	21.50	523.50	
68	548	07/02/03	9.37	538.63	
		11/15/03	9.87	538.13	
69	551	07/02/03	8.66	542.34	pumping in progress during water level measurement
72	635	11/08/03	13.58	621.42	

bls = below land surface
asl = above sea level

Appendix E: Basic Groundwater Chemistry

Basic groundwater chemistry data were collected in the field during the well survey and water level measurements. The parameters measured were total dissolved solids (TDS), pH, temperature, and nitrate concentration. A MyronL Company Ultrameter was used to collect TDS, pH, and water temperature data. A ChemMetrics VVR multi-analyte photometer and nitrate VACU-vials were used to measure nitrate concentration. This kit was designed to produce the most accurate results when nitrate concentration is less than 70 ppm NO_3 as NO_3. Following are the results of these measurements.

Well Number	DATE	Nitrate (ppm as NO3)	Temperature (degrees C)	Total Dissolved Solids (ppm)	pH	Comments
2	06/14/03		21.8	494.3	7.01	
3	06/14/03		23.1	1027.0	7.39	
	11/08/03	> 70.0	19.4	1014.0	7.59	
4	06/16/03		23.3	805.1	7.35	
	11/08/03	68.0	19.6	1041.0	7.13	
7	06/17/03		29.2	466.7	7.55	water sample collected from tap
8	06/17/03		23.4	459.1	7.09	
	11/11/03	> 70.0	22.6	456.5	7.08	
9	06/17/03		24.3	445.3	7.09	
10	06/18/03		23.5	305.1	7.75	
	11/08/03	18.5	19.4	558.5	7.59	
12	06/18/03		24.0	777.8	7.36	
13	06/18/03		24.1	545.6	7.14	
	11/08/03	50.5	19.9	605.2	7.17	
14	06/19/03		26.0	885.0	6.81	
	11/06/03	6.5	16.9	675.5	7.26	
17	06/19/03		23.0	454.7	6.98	
	11/11/03	> 70.0	21.7	471.4	7.08	
18	06/19/03		24.4	589.6	6.97	
	11/15/03	> 70.0	22.9	543.0	7.01	
21	06/20/03		22.4	582.2	6.96	
	11/06/03	> 70.0	19.2	553.3	7.23	
23	06/21/03		23.3	436.7	7.26	
25	06/23/03		22.6	401.2	7.34	
	06/27/03		23.2	382.6	7.27	
	11/08/03	39.5	19.9	463.0	7.58	
26	06/23/03		26.1	478.3	7.02	
	06/27/03		25.4	442.4	7.12	
	11/08/03	42.5	18.9	467.8	7.26	
27	06/23/03		26.6	449.6	7.17	
	06/27/03		26.2	418.1	7.29	
	11/08/03	59.0	20.0	456.4	7.13	
28	06/23/03		24.4	416.2	7.17	
	06/27/03		24.5	406.1	7.26	
	11/08/03	>70.0	19.2	471.5	7.20	
31	06/25/03		24.0	120.3	7.31	
36	11/06/03	> 70.0	19.7	470.7	7.20	
41	11/06/03	> 70.0	18.7	491.0	7.41	
47	11/15/03	5.5	20.9	427.3	7.34	
49	06/28/03		22.4	505.7	7.42	
	11/06/03		19.8	494.7	7.65	

Well Number	DATE	Nitrate (ppm as NO3)	Temperature (degrees C)	Total Dissolved Solids (ppm)	pH	Comments
50	06/28/03		22.8	502.5	7.03	
	11/06/03	3.5	19.5	552.6	7.13	
52	06/28/03		24.3	440.6	7.41	
	11/06/03	38.0	20.4	756.7	7.14	
53	06/28/03		25.7	759.6	7.62	
	11/06/03	23.5	19.0	639.4	7.66	
54	06/28/03		25.4	660.8	6.92	water sample collected from tap
55	11/11/03	13.0	25.4	1506.0	7.08	
56	06/28/03		27.8	614.0	6.95	
57	06/30/03		25.4	400.3	7.34	
58	06/30/03		25.3	462.8	6.93	water sample collected from tap
	11/15/03	5.0	23.2	501.7	6.91	water sample collected from tap
60a	07/01/03		24.1	756.0	7.13	water sample collected from tap
61	07/01/03		24.9	498.2	7.40	
62	07/01/03		24.2	550.6	7.60	
64	11/11/03	38.0	22.4	1143.0	7.00	water sample collected from tap
66	07/02/03		23.6	468.1	6.96	
72	11/08/03	48.5	19.6	420.3	7.29	

Appendix F: Basic Surface Water Chemistry

Basic water chemistry data were collected in the field from several points along Clear Fork Plum Creek, Boggy Creek, Hemphill Creek, Town Branch, and a pool in an abandoned gravel pit. The location of these measurements are shown on Figure A-1. The parameters measured were total dissolved solids (TDS), pH, temperature, and nitrate concentration. A MyronL Company Ultrameter was used to collect TDS, pH, and water temperature data. A ChemMetrics VVR multi-analyte photometer and nitrate VACU-vials were used to measure nitrate concentration. This kit was designed to produce the most accurate results when nitrate concentration is less than 70 ppm NO_3 as NO_3. Following are the results of these measurements.

Number	Surface Water Body	Elevation of Land Surface (ft asl)	DATE	Nitrate (ppm)	Temperature (degrees C)	Total Dissolved Solids	pH
5	Clear Fork Plum Creek	609	06/16/03		27.9	297.1	7.64
		610	11/08/03	3.5	15.0	372.6	7.80
6	Hemphill Creek	570	06/16/03		31.9	441.5	8.13
15	Boggy Creek	501	06/19/03		24.0	442.8	7.68
		501	11/06/03	41.0	19.8	464.2	7.65
16	Clear Fork Plum Creek	499	06/19/03		25.7	420.0	7.81
		499	11/06/03	30.0	20.5	530.7	7.66
51	Abandoned Gravel Pit	561	06/28/03		28.9	421.1	7.02
		561	11/06/03		17.9	498.5	6.88
70	Clear Fork Plum Creek	571	11/06/03	19.5	17.8	456.0	8.12
71	Clear Fork Plum Creek	576	11/06/03		18.2	526.2	7.65
73	Town Branch	502	11/22/03	32.0			

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